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Test method

Characterisation of torsional actuation in highly twisted yarns and fibres

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ABSTRACT

Highly twisted oriented polymer fibres and carbon nanotube yarns show large scale torsional actuation from volume expansion that can be induced, for example, thermally or by electrochemical charging. When formed into spring-like coils, the torsional actuation within the fibre or yarn generates powerful tensile actuation per muscle weight. For further development of these coil actuators and for the practical application of torsional actuators, it is important to standardise methods for characterising both the torsional stroke (rotation) and torque generated. By analogy with tensile actuators, we here introduce a method to measure both the free stroke and blocked torque in a one-end-tethered fibre. In addition, the torsional actuation can be measured when operating against an externally applied torque (isotonic) and actuation against a return spring fibre (variable torque). A theoretical treatment of torsional actuation was formulated using torsion mechanics and evaluated using a commercially available highly-oriented polyamide fibre. Good agreement between experimental measurements and calculated values was obtained. The analysis allows the prediction of torsional stroke under any external loading condition based on the fundamental characteristics of the actuator: free stroke and stiffness.

1. Introduction

Giant torsional actuation from highly twisted fibres and yarns has been recently discovered [1–6], with potential applications in microfluidic mixing [1] and digital displays [3]. Volume expansion induced thermally, chemically, photonically or electrochemically causes partial untwisting of highly twisted carbon nanotube, graphene or oriented polymer fibres and yarns [1,6]. Rotations per actuator length of such twisted structures were 1000 times larger than previously reported systems [7,8]. Additionally, it was discovered that when the torsionally-actuating fibres and yarns are converted to coils, for example by extreme twist insertion, the fibre untwist translates to expansion or contraction along the coil axis. Tensile strokes as high as 49% were reported for twisted and coiled nylon-6,6 fibres delivering 2.48 kJ kg^{-1} contractile work capacity [6] and greatly exceeding that generated by natural skeletal muscle (39 J kg^{-1}) [9,10].

To aid material development for torsional muscle, the present work aims to develop a test method for assessing torsional actuation. Of interest is a procedure to characterize torsional stroke and torque as well as an assessment of speed, reversibility and cycle life. Previous work has focussed mainly on measuring torsional stroke, for example by tethering the sample at one end and measuring the rotation of the free end. Sometimes a return spring mechanism has been used to improve reversibility of torsional actuation. In these cases, the actuating yarn or fibre was attached to another non-actuating fibre, both ends were tethered and torsional rotation measured at the junction. An advantage of the two-end-tethered system is the ability to fix the location of the rotating element. In contrast, the free end of the one-end-tethered system can move in any direction and has limited practical utility.

What is needed is a measurement technique and analysis procedure that allows the torsional stroke and torque to be calculated for any imposed external loads. By analogy with tensile actuators, the characterisation method should provide the stroke–torque

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curve defining the free stroke (zero external torque), blocked torque (zero torsional rotation) and all combinations of non-zero stroke and torque. Such information has not yet been reported for any of the twisted fibre torsional muscles. Herein is described a method for measuring the rotation of a shaft attached to a near frictionless bearing and driven by a torsional actuator, *i.e.* the twisted fibre. The measurement system can measure both torsional stroke and torque, and the sample can either be operated with or without a return spring fibre.

The theoretical treatment of torsional actuation assumes that a given stimulus induces a free rotation that increases linearly with fibre length, and is here denoted θ and reported as degrees per mm of actuating fibre length. The actual rotation angle $\phi(x)$ varies linearly with distance x taken from the clamped end of a fibre so that the torsional stroke at the free end of a one-end-tethered fibre of length L_A is:

$$\phi(L_A)_{free} = L_A \cdot \theta \tag{1}$$

If the fibre behaves as a linear elastic rod in torsion, then the blocked torque will be:

$$\tau_{blocked} = \phi(L_A)_{free} \times S_A \tag{2}$$

here, S_A is the torsional rigidity of the actuating fibre, or the resistance to rotation. The torsional stiffness is more fundamentally related to the fibre diameter (d), length (L) and the fibre material's shear modulus (G) in the circumferential direction:

$$S = \frac{k}{L} = \frac{JG}{L} \tag{3}$$

where, k is termed the 'torsional modulus' in standard torsion mechanics and should not be confused with other moduli, such as the shear modulus and Young's modulus that are true material properties. The torsional modulus depends both on material properties and the fibre dimensions. J is the polar moment of inertia of the fibre and formulated in terms of sample diameter for a fibre of circular cross-section is:

$$J = \frac{\pi d^4}{32} \tag{4}$$

The stimulus used to initiate torsional actuation, for example heat, is likely to affect the material's torsional stiffness due to dimensional changes and modulus shift. Consequently, the blocked torque represented by Equation (2) uses the torsional stiffness of the fibre in the final actuated state after the stimulus has been applied (hereafter denoted S'_A). A change in torsional stiffness will also contribute to the torsional stroke measured under isotonic (constant external torque) conditions. For a one-end-tethered fibre acting against an external torque τ_{ext} the torsional stroke will be given by:

$$\phi(L_A)_{isotonic} = L_A\theta + \tau_{ext}\left(\frac{1}{S'_A} - \frac{1}{S_A}\right) \tag{5}$$

The second term in Equation (5) relates to the free end rotation resulting from a change in sample torsional stiffness from S_A to S'_A in the starting and final states, respectively.

When operated against a return spring, the external torque acting against the actuating fibre increases after the stimulus has been applied. The return spring is twisted as the actuating fibre torsionally actuates generating a restoring torque within the return spring fibre. The rotation at the end of the actuating fibre, corresponding to the junction between the actuating and non-actuating fibres, will be smaller than in free rotation so a residual torque remains in the actuating fibre. At equilibrium, the residual torque in the actuating fibre is exactly cancelled by the restoring torque generated in the return spring, non-actuating fibre. For the general case where the actuating fibre is subjected to a constant external torque and connected to a return spring fibre of torsional stiffness S_N, the torsional stroke (ϕ) at the junction between actuating and non-actuating fibres can be determined from the torque balance equation:

$$S'_A\left[\left\{L_A\theta + \tau_{ext}\left(\frac{1}{S'_A} - \frac{1}{S_A}\right)\right\} - \phi\right] = S_N\phi \tag{6}$$

Re-arranging Equation (6) gives an expression for the expected torsional stroke at the junction between the actuating and non-actuating fibres:

$$\phi(L_A)_{return\ \ spring} = \left[L_A\theta + \tau_{ext}\left(\frac{1}{S'_A} - \frac{1}{S_A}\right)\right]\left(\frac{S'_A}{S'_A + S_N}\right) \tag{7}$$

In the case where the external torque is zero, the stroke is given by:

$$\phi(L_A)_{return\ \ spring} = L_A\theta\left(\frac{S'_A}{S'_A + S_N}\right) \tag{8}$$

Equation (8) reduces to Equation (1) in the absence of a return spring ($S_N = 0$) and when the actuating fibre is tethered at only one end. Fig. 1 illustrates the theoretical torsional stroke expected for the case of free rotation, isotonic torsional actuation and torsional actuation with a return spring. The torsional strokes are expressed as a fraction of the free rotation to emphasise the importance of the inherent torsional actuation parameter, θ, in determining the torsional stroke in all cases.

2. Experimental methods

2.1. Muscle fabrication

Twist insertion into commercially available nylon 6 fibre (~550 μm diameter Sport Fisher monofilament fishing line) was conducted by an electrical DC motor. The fibre was attached to the motor at its upper end and supported by a fixed weight (~200 gm) hanging on the other end providing 10 MPa stress to the fibre. The incorporated weight was tethered contrary to the motor rotation, and hence each turn from the motor shaft caused the formation of one turn in the fibre. The muscle fibre taken for the actuation test was twisted until the onset of coiling. The supported weight on the fibre was crucial to have straight and uniformly twisted fibres, without permitting snarl formation prior to coiling. The non-coiled section of twisted fibre was then taken to an isothermal heating oven and annealed at 120 °C, or ~70 °C above glass transition (T_g) [11,12], for 30 min with both ends clamped to prevent loss of twist. Heating at a temperature over T_g helps the newly introduced twisted shape to be permanently set. After removal from the oven, the fibre was relaxed at room temperature for 2 h while still clamped. Fig. 2 shows a schematic diagram of twist insertion and the preparation of fishing line muscle to be used for actuation tests.

Twist insertion per length of precursor fibre was determined by using a rotation counter. Fibre bias angle (α_f, relative to fibre axis) due to the twist insertion was calculated from the number of turns/meter using Equation (9) [1].

$$\alpha_f = tan^{-1}(\pi dT) \tag{9}$$

here, d is the fibre diameter and T is the amount of turns inserted per initial fibre length.