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Twist–coil coupling fibres for high stroke tensile artificial muscles

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ABSTRACT

A new concept for tensile artificial muscles is introduced in which the torsional actuation of a twisted polymer fibre drives a twist to writhe conversion in a serially attached elastomeric fibre. Thermally induced torsional rotation of the twisted fibre caused formation of coils in the elastomeric fibre which resulted in overall muscle length contraction. Theoretical predictions of the muscle strain were developed by means of a modified single-helix theory. Experimental tests were conducted to measure the isotonic contraction strains for elastomeric fibres of different diameters and lengths. A good agreement between the measured and calculated results was found. Practical applicability of this muscle is evaluated by using different mechanical loading conditions. Actuation contraction strains as high as 10% were observed with excellent reversibility. Unlike original coiled fibre tensile actuators, these twist-coil artificial muscles did not require any pre-conditioning cycles.

1. Introduction

The idea of an artificial muscle dates back several decades with many materials now demonstrating volume and / or shape changes when stimulated [1–4]. General advantages of artificial muscles include their noiseless operation and capacity for miniaturisation without loss in power output per weight [5]. Artificial muscles have also been reported with three primary types of actuation: bending [6,7], tensile [8,9] and torsional [8,10,11]. Diverse applications of these muscles have been proposed ranging from soft robotics [12], prosthetic limbs [13], smart textiles [8,9], exoskeletons [14], miniature fluidic mixers [2,8], photonic displays [15], and energy harvesting devices [10].

Torsional artificial muscles made from twisted polymer fibres have created much interest, mainly because they are the basis for high performance tensile actuation when the twisted fibres are formed into helical coils [8,10,16–19]. Torsional actuation can be induced in twisted fibres by a volume change, such as thermal expansion. The thermally induced untwisting of drawn and twisted semicrystalline polymer fibres can be explained based on their anisotropic thermal properties where the untwisted fibres show comparatively large diameter expansion and negligible length direction change due to the high stiffness along the polymer chain axis. Twisting of these fibres results in helically oriented chains so that volume increases are accommodated by a partial fibre untwist. Thermal expansion and associated torsional actuation of twisted nylon-6 fibres have been successfully modelled using a single helix geometry with the assumption that the polymer chains are inextensible [20]. In the systems where twisted fibres are mechanically converted to coiled structures, the torsion that accompanies volume expansion of the twisted fibre is translated into a length change in the coil. Tensile strokes as high as 50% have been observed [8].

Here, we report a new mechanism of torsion driven tensile actuation, which is schematically illustrated in Fig. 1. A torsionally active non-coiled fibre is coupled in series with a second fibre that has a low critical torque for twist-induced coil formation. Significant overall length contraction occurs as coil turns form in the latter fibre due to the rotation of the torsionally active fibre. This effect can be optimised by adjusting the relative lengths of the fibres with respect to each other.

The overall length contraction (ΔL_{total}) of the twist-coil actuator is the summation of length changes in the elastomeric fibre (due to coil formation) and the twisted fibre (due to untwisting). In the former case, the length change as a result of coil formation can be predicted using the geometry of a single helix. Fig. 1 shows the schematic illustration of the twist-coil actuator arrangement. The total length before stimulation (L_{total}) comprised the elastomer fibre length (l_N) and the length of the torsionally-active twisted polymer fibre (l_A). For each coil turn that forms, a straight segment

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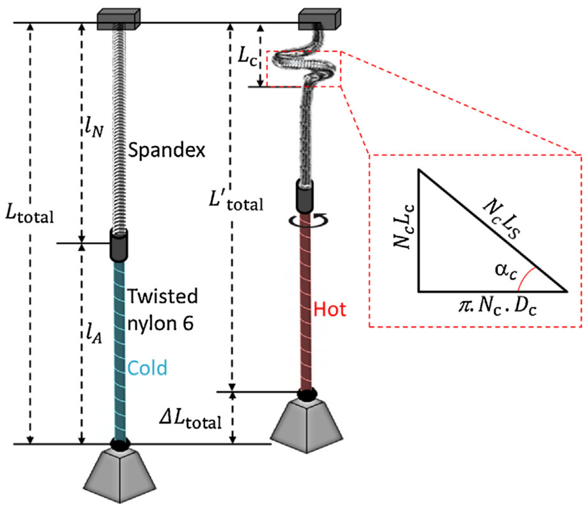

Fig. 1. Schematic illustration of the twist-coil actuator system: a torsionally active fibre (twisted nylon 6) is heated to cause rotation at the junction with a serially connected second fibre (Spandex). This rotation results in coil turn formation and linear, tensile contraction. The geometry of the coil turns is illustrated as an opened-up single-helix to show the relationships between torsional rotation and tensile contraction.

of elastomeric fibre of length L_S is converted to a coil of length L_c. Assuming that the contour lengths of both the elastomeric fibre and the twisted polymer fibre remain unchanged, then the formation of N_c coil turns in the elastomeric fibre causes an overall length change given by:

$$\Delta L_{total} = N_c\left(L_c - L_s\right) = N_c\left(\pi D_c \tan\alpha_c - \frac{\pi D_c}{\cos\alpha_c}\right)$$
$$= \pi N_c D_c \frac{(\sin\alpha_c - 1)}{\cos\alpha_c} \quad (1)$$

where D_c is the coil diameter and α_c is the coil bias angle taken against the perpendicular direction to the long axis of the elastomeric return spring fibre. Here, ΔL_{total} is the contraction of the elastomeric fibre which also represents the overall tensile stroke of the series muscle since the length change during torsional actuation of the twisted fibre has been found to be negligible in previous studies [20].

Twist induced coil formation in fibres, wires and cables have been investigated using torsion mechanics [21,22]. Here, the critical torque (τ_c) needed to initiate coiling in the second fibre was estimated based on the criterion of Ross [23]:

$$\tau_c = \sqrt{2EIF} \quad (2)$$

where E is the tensile modulus, I is the second moment of area of the coiling fibre and F is the applied tensile force. For fibres of circular cross-section and diameter D_y, the second moment of area is $\pi D_y{}^4/64$. Based on Eq. 2, coil formation is favoured in thin fibres of low elastic modulus. For this reason, a soft elastomeric fibre (commercially-available Spandex fibre) was used in the current work as the tensile actuator. The torsion was induced by heating a twisted and annealed nylon 6 fibre, as described previously [24]. The free torsional stroke per fibre length (ΔT_{free}) and generated blocked torque ($\tau_{blocked}$) of a twisted fibre when stimulated can be described by [24]:

$$\Delta T_{free} = \frac{n_o}{l_A}\left(\frac{d_o}{d} - 1\right) \quad (3)$$

$$\tau_{blocked} = \Delta T_{free} \times J_A G_A \quad (4)$$

where n_o is the initially inserted twist (turns) in the fibre having an initial length l_A; d_o and d are the fibre diameters before and after heating; and $J_A G_A$ is the torsional modulus of the twisted fibre after heating; G_A is the fibre shear modulus after heating and J_A is the polar moment of area which is $\pi d^4/32$ for fibres of circular cross-section. Eq. 3 predicts the 'free', or unimpeded, torsional stroke. However, the attached Spandex fibre acts as a return spring (torsional modulus, $J_N G_N$; length, l_N) as described previously [2,24] and reduces the torsional stroke of the twisted fibre:

$$\Delta T = \Delta T_{free}\left(\frac{J_A G_A}{J_A G_A + \frac{l_A}{l_N}\left(J_N G_N\right)}\right) \quad (5)$$

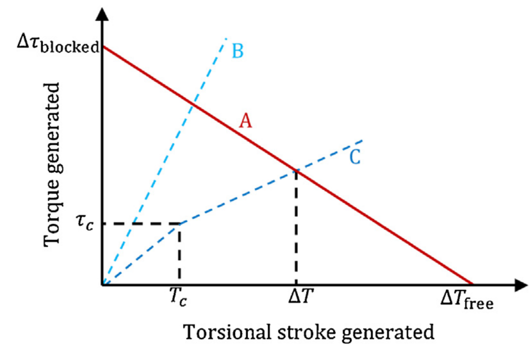

Fig. 2. Schematic illustration of the mix of torque and torsional stroke generated by a torsional actuator when activated (line A). The final torque and stroke generated depends on the external loading conditions. Free rotation generates the largest torsional stroke ($\Delta \boldsymbol{T}_{\mathbf{free}}$) and blocked rotation generates the largest torque ($\Delta \boldsymbol{\tau}_{\mathbf{blocked}}$). The torsional properties of non-coiling and coiling return spring fibres are represented by lines B and C, respectively.

The full range of generated torsional strokes and torques can be represented by the torque – stroke curve as shown schematically as line A in Fig. 2. The effect of a return spring fibre is illustrated by the dashed line B having a slope equivalent to the torsional stiffness of the return spring. The intersection of lines A and B represent the final torsional stroke and residual torque applied by the torsional actuator on the return spring. The case of a return spring fibre that forms a coil when connected in series to a torsional actuator is represented by line C. For clarity of presentation, this return spring is shown with a lower stiffness than the non-coiling return spring represented by line B. When the first coil appears, the torsional stiffness of the coiling return spring decreases as shown by the discontinuous slope of line C. This first coil turn forms when the torque acting on the return spring reaches the critical torque (τ_c) or equivalently the critical twist ($l_N T_c$) inserted in the return spring fibre. The number of turns formed in the coil (N_c) depends on the remaining torsional stroke after the initiation of the first coil formation, so that:

$$N_c = \left(l_A \Delta T - l_N T_c\right) \quad (6)$$

Combining Eqs. (1) and (6) gives the final predicted tensile stroke for the series actuator:

$$\Delta L_{total} = \pi D_c\left(l_A \Delta T - l_N T_c\right)\frac{(\sin\alpha_c - 1)}{\cos\alpha_c} \quad (7)$$

A series of experiments were conducted using different lengths of Spandex fibre return spring and nylon 6 torsionally active fibres to evaluate Eq. (7). The length of each fibre affects the expected torsional stroke as described in Eq. (4): the torsional stiffness of the fibres depends inversely on fibre length, and the torsional free stroke of the actuating fibre is proportional to actuating fibre length. The tensile stroke is expressed as a percentage of the initial unloaded length of the series actuator to effectively compare the performance of different length combinations. The effect of the applied external load on coil formation and tensile stroke is also considered.