HIGH PERFORMANCE, ELECTROLYTE-FREE TORSIONAL AND TENSILE CARBON NANOTUBE YARN COMPOSITE MUSCLES

M. Lima[1], N. Li[1,2], M. Andrade[1], S. Fang[1], J. Oh[1], G. Spinks[3], M. Kozlov[1], C. Haines[1], D. Suh[1], J. Foroughi[3], S. Kim[4], Y. Chen[2], T. Ware[1], M. Shin[4], L. Machado[5], A. Fonseca[6], J. Madden[7], W. Voit[1], D. Galvão[5], R. H. Baughman[1]*

[1] NanoTech Institute, The University of Texas at Dallas, Richardson, USA; [2] Institute of Polymer Chemistry, Nankai University, Tianjin, China; [3] Intelligent Polymer Research Institute, University of Wollongong, Wollongong, Australia; [4]Department of Biomedical Engineering, Hanyang University, Seoul, South Korea; [5]Applied Physics Department, State University of Campinas – UNICAMP, São Paulo, Brazil; [6] Faculdade de Ciências, UNESP–Univ. Estadual Paulista, Bauru, SP, Brazil; [7] Department of Electrical and Computer Engineering, University of British Columbia, Canada.

* Corresponding author: Ray H. Baughman (ray.baughman@utdallas.edu)

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1 General Introduction

The concept of deploying strong carbon nanotube yarns as actuators has produced both electrochemically and thermally powered yarn muscles. The performance of electrochemically powered yarn muscles [1, 2] is adversely affected for most applications by the need for electrolyte, counter electrode, and device packaging, which add much more to actuator weight and volume than the actuating electrode. The electrolyte also limits operating temperature and voltage, as well as actuation rate. Previous work has demonstrated use of polymer-filled non-twisted carbon nanotube yarns as thermally powered shape memory actuators, but reversible actuation was not achieved [3]. Dispersed carbon nanotubes and nanotube sheets have been used for electrically heating thermally actuating materials to provide cantilever deflections [4, 5, 6].

2 Summary of Results

New electrolyte-free muscles that provide fast, high-force, large-stroke torsional and tensile actuation are described which are based on guest-filled, twist-spun carbon nanotube yarns [7]. Actuation of hybrid yarns by electrically, chemically, and photonically powered dimensional changes of yarn guest generates torsional rotation and contraction of the helical yarn host. Over a million reversible torsional and tensile actuation cycles are demonstrated, wherein a muscle spins a rotor at an average 11,500 revolutions/minute or delivers 3% tensile contraction at 1,200 cycles/minute. The 27.9 kW/kg power density during muscle contraction is 85 times higher than for natural skeletal muscle. Applying well-separated 25 ms pulses yielded 0.104 kJ/kg of mechanical energy during contraction at an average power output of 4.2 kW/kg (four times the power-to-weight ratio of common internal combustion engines). Actuator configurations and yarn types shown in Figure 1 are used to optimize tensile and torsional actuation and cycle life. Yarn over twist to provide yarn coiling is especially important for realizing high actuation stroke. Even without guest filling, coiling increases the negative thermal expansion of a neat twist-spun yarn by a factor of ~10. Since these coiled neat yarns provide up to 7.3% hysteresis-free contraction when lifting heavy loads using temperature changes up to ~2,500^{o}C, these muscles can be deployed in inert atmosphere to temperatures where no other high work capacity actuator can survive. Demonstrations include torsional motors, contractile muscles, and sensors that capture the energy of the sensing process to mechanically actuate. Improved control and large rotational actuation, along with long cycle life and tensile contractions up to 9%, suggest the use of these yarn actuators in medical devices, robots, and shutters, for which shape memory alloys are currently employed, as well as extension to microvalves, mixers, smart phone lenses, positioners and even toys and intelligent textiles.

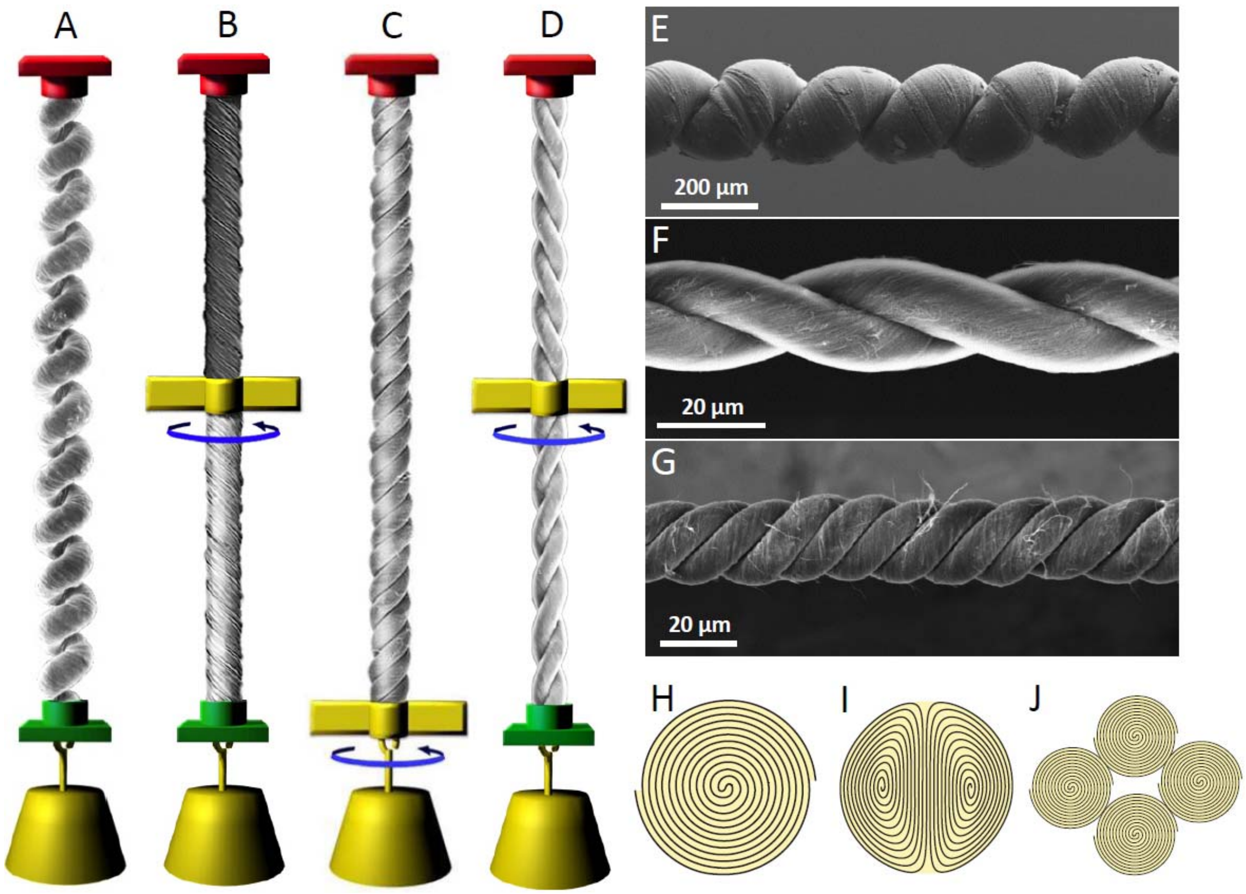

Fig. 1. Muscle configurations and yarn structures for tensile and torsional actuation. Tensile load and paddle positions for (A) a two-end-tethered, fully-infiltrated homochiral yarn; (B) a two-end-tethered, bottom-half-infiltrated homochiral yarn; (C) a one-end-tethered, fully-infiltrated homochiral yarn; and (D) a two-end-tethered, fully-infiltrated heterochiral yarn. The depicted yarns are coiled, non-coiled, four-ply, and two-ply, respectively. Arrows indicate the observed direction of paddle rotation during thermal actuation. Red and green yarn-end attachments are tethers, meaning they prohibit end rotation – red attachments also prohibit translational displacement. SEM micrographs of (E) a fully-infiltrated homochiral coiled yarn, (F) a neat two-ply yarn, and **(**G) a neat four-ply yarn. Illustration of ideal cross-sections for (H) Fermat, **(**I) dual-Archimedean, and (J) infiltrated four-ply Fermat yarns.

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