Journal of the Mechanical Behavior of Biomedical Materials 75 (2017) 228–235

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

journal homepage: www.elsevier.com/locate/jmbbm

Design and characterization of a hyperelastic tubular soft composite

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ARTICLE INFO

Keywords:
Soft composite
Pneumatic artificial muscle
Passive actuator
Mobility assistive devices
Exoskeleton

ABSTRACT

Research in the field of human mobility assistive devices, aiming to reduce the metabolic cost of daily activities, is seeing the benefits of the exclusive use of passive actuators to store and release energy during the gait cycle. Current devices commonly employ either mechanical springs or Pneumatic Artificial Muscles as the primary method of passive actuation. The Pneumatic Artificial Muscle has proven to be a superior actuation choice for these devices, when compared to its alternatives. However, challenges regarding muscle pressure loss and limited elongation potential have been identified. This paper presents a hyperelastic tubular Soft Composite that replicates the distinctive mechanical behaviour of the Pneumatic Artificial Muscle without the need for internal pressurization. The proposed Soft Composite solution is achieved by impregnating a prefabricated polyethylene terephthalate braided sleeve, held at a high initial fibre angle, with a silicone prepolymer. A comprehensive experimental evaluation is achieved on numerous prototypes for a variety of customizable design parameters including: the initial fibre angle, the silicone stiffness, and the braided sleeve style. This research has successfully developed, tested, and validated a novel Soft Composite that can achieve the desired nonlinear stiffness and elongation potential for optimal use as passive actuation in human mobility assistive devices.

1. Introduction

Previous and current work in the field of human mobility assistive devices (Ferris et al., 2005; Collins et al., 2015) has demonstrated the benefits of using passive actuators to store and release energy during the gait cycle. Designs of novel passive exoskeletons, aiming to reduce the metabolic cost of daily activities, are ongoing endeavours that distinctively implement the Pneumatic Artificial Muscle (PAM) (Wiggin et al., 2011; Doumit and Leclair, 2017) as the primary method of nonlinear passive actuation. The PAM is a soft pneumatic actuator that provides ideal nonlinear mechanical stiffness properties for this application, however, challenges regarding pressure dissipation over prolonged use, and a limitated elongation range of 30% of its contracted length (Doumit et al., 2009) have delimited its potential.

This has motivated the design and development of a novel passive actuation device with mechanical properties comparable to the PAM while not requiring internal pressurization. The desired passive elastic behaviour, analogous to that of biological connective tissue, is described by a force-elongation response consisting of an initial toe region and subsequent linear region. Mechanical devices that exhibit these desired properties have been previously seen in use as artificial ligament replacements and various soft robotic applications in the form of a hyperelastic tubular Soft Composite (SC).

1.1. Background

Hyperelastic tubular SC designs were initially proposed as ligament prostheses using hydrogel polymer matrices reinforced with polyethylene teraphthalate (PET) fibres in the mid to late 1990's (Iannace et al., 1995; Ambrosio et al., 1998a, 1998b). In studies as recent as 2013, Thayer et al. (2013) proposed a hydrogel SC design for ligament tissue engineering. The group suggested that electrospun poly-lacticco-glycolic acid or poly(ester urethane)urea meshes formed into composites with a polyethylene glycol hydrogel matrix could withstand cyclic loading from gait stimulus. Furthermore, in 2014, Lou et al. (2014) presented a study examining open-meshed tubular braided composites consisting of PET fibres in a gelatin matrix. Through tensile strength tests of the composite, it was found that the increase in gelatin concentration resulted in a decreased tensile displacement but did not change the tensile strength of the composite. Lou et al. (2014) carried out the same studies on a polylactic acid (PLA)/spandex hybrid braid immersed into a gelatin solution. It was found that an increase in the density of the PLA yarns resulted in an overall increase of tensile strength of the composite, whereas the increase in spandex yarn density had no such effects.

Early accounts of hyperelastic SCs used as artificial ligament prostheses were seen in the work of Iannace et al. (1995) where they based their material on a hydrogel polymer matrix reinforced with bundles of

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http://dx.doi.org/10.1016/j.jmbbm.2017.07.031
Received 4 April 2017; Received in revised form 18 July 2017; Accepted 21 July 2017
Available online 22 July 2017
1751-6161/

PET fibres. They wound a bundle of PET fibres helically around a polyethylene hose while simultaneously coating it with a matrix material, plasticizer, and a cross-linking agent. Multiple specimens with unique initial fibre angles of 19° and 35° were then separately inserted into a Teflon tube which was filled with the prepolymer matrix composed of 2-hydroxyethyl methacrylate. The impregnated mold was allowed to cure for 60 min at 90 °C and then demolded to yield the final SC specimen.

Iannace et al. (1995) concluded that the increase in the initial fibre angle mainly influenced the length of the critical deformation, and had a lesser effect on the slope of the toe region of the SC. They specified that the response of the SC within the toe region was mainly governed by the properties of the matrix while the response within the linear region was primarily attributed mainly to the properties and geometry of the fibres. They also stated that an increase in the matrix rigidity resulted in a stiffer toe and linear region response.

Another type of prosthetic ligament was created by Mollica et al. (2006) that used a similar fabrication method to Iannace et al. (1995). The group helically wound a bundle of PET fibres, composed of 192 monofilaments, around a steel mandrel with a filament winding machine. Some of the PET fibres were plasma treated prior to winding so that their respective specimens could later be compared to those with the untreated PET fibres. The PET fibres were impregnated with 2-hydroxyethyl methacrylate and dimethylacetamide in an 18/72% ratio, by weight, prior to the braiding process. Composite specimens were kept under a hood vent for 24 h to cure, then they were placed in a distilled water bath for 24 h, at room temperature. Specimens were created with initial fibre angles of 20° and 40° and with different fibre volume fractions. The specimens were then tested in simple tension on an Instron dynamometer at a speed of 3 mm s^{-1} at room temperature.

The major contributor to the property variance of the SC was the initial fibre angle. Mollica et al. (2006) illustrates the gross difference in the length of the toe region for specimens with initial fibre angles of 20° and 40°. It was determined that the plasma treatments created a better fibre-to-matrix interface, and resulted in a stiffer composite with a shorter toe region in its response curve. Evidence of this behaviour is depicted in Mollica et al. (2006) which illustrates the contrast between the plasma treated fibres and their non-treated counterparts.

Researchers are currently experimenting with ways to fabricate soft actuators for a variety of delicate applications (Roche et al., 2014), where more common mechanical actuators would be risking safety or performance. Some initiatives involve wrapping the PAM with an elastomeric layer (Faudzi et al., 2012) while other, more recent advances have been coating the entire PAM with an elastomer to create a SC (Roche et al., 2014; Faudzi et al., 2012; Obiajulu et al., 2013).

A simple method to manufacture hyperelastic tubular braided SCs, with the intent of being internally pressurized, was outlined by Obiajulu et al. (2013). They used off-of-the shelf PET tubular braids and a prepolymer mix to fabricate a SC actuator. Two different prepolymers, each with a different stiffness, were used to make separate classes of actuators. The fabrication method involved fitting the PET braid over an inner tube and then coating the entire apparatus with the elastomer to yield a soft actuator.

The inner tubing was created by mixing a prepolymer and pouring it into a plastic mold. The mold was then degassed in a vacuum chamber for 10 min at an absolute pressure of 10 kPa, then it was cured in a pressure chamber heated to 90 °C for 60 min. The inner tube was demolded and was fitted into a PET braided sleeve. To complete the SC actuator, the PET sleeve (fitted with the inner tube) was coated with more elastomer and cured using a heat gun. Plugs on either end were created and a stylet was inserted into one end for air to be added or released. An example of the possible applications for these SC actuators can be seen in the work of Roche et al. (2014). More specifically, they utilized the SC as an active actuator to assist with left-ventricular cardiac contraction.

The open literature survey presented in this section has shown that different forms of a SC have been developed and analysed for a variety of applications. The aforementioned alternatives and related applications, however, greatly differ from the current requirements needed in human mobility assistive devices. The key properties of the SC must therefore be further investigated in order to optimize its performance as a nonlinear passive actuator for the currently proposed application.

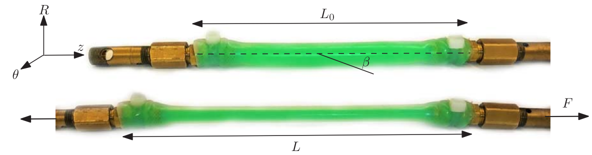

Fig. 1. A SC specimen made with a regular braid and soft silicone matrix shown in a resting (top) and stretched (bottom) configuration.

1.2. Objectives

This work aims to develop a hyperelastic, tubular SC that replicates the distinct mechanical behaviour of the PAM without the need for internal pressurization. The proposed SC must exceed the PAM's elongation range of 30% of its contracted length. Furthermore, this work aims to achieve an experimental characterization of the SC as a basis for a development method which will help designers select specific SCs that meet the actuation requirements of passive human mobility assistive devices.

The proposed SC, presented in Fig. 1, consists of a braided sleeve that is embedded into an elastomeric matrix. The operation of the SC is simple. As either end of the SC is elongated an axial force is developed, and the embedded fibres begin to align parallel to the applied force. The axial force of the SC continues to increase nonlinearly with the elongation until it reaches its maximum state and then fails.

2. Methodology

A multi-step methodology was used to guide research activities. First, a SC specimen was designed and fabricated. This step considered the fabrication process, the types of materials used for fabrication, and the key input control parameters that dictate the mechanical behaviour of the SC. Next, the mechanical behaviour of the SC was experimentally evaluated through a selection of testing protocols.

2.1. SC Development

The development of the proposed SC was primarily motivated by the objective of converting the PAM into a passive fluidless actuator. Fig. 2 shows a PAM prototype that was fabricated in laboratory, by Doumit et al. (2009), which consists of an elastic bladder wrapped by a braided mesh and secured with end fixtures. Maintaining the governing geometric relationship offered by the PAM braid was paramount to the design while also removing the need of a fluid supply, thereby avoiding pressure dissipation over time. This objective was accomplished by embedding an elastomer between the braided fibres.

The secondary objective was to create a SC specimen with an elongation potential greater than that offered by the PAM which is only 30% of its contracted length (Doumit et al., 2009). The contraction


Fig. 2. Deflated (top) and inflated (bottom) PAM (Doumit et al., 2009).