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Research Paper

Parametric elastic analysis of coupled helical coils for tubular implant applications: Experimental characterization and numerical analysis

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ABSTRACT

Coupled helical coils show promising mechanical behavior to be used as tubular organ constructs, e.g., in trachea or urethra. They are potentially easy to manufacture by filament winding of biocompatible and resorbable polymers, and could be tailored for suitable mechanical properties. In this study, coupled helical coils were manufactured by filament winding of melt-extruded polycaprolactone, which was reported to demonstrate desired in vivo degradation speed matching tissue regeneration rate. The tensile and bending stiffness was characterized for a set of couple helical coils with different geometric designs, with right-handed and left-handed polymer helices fused together in joints where the filaments cross. The Young's modulus of unidirectional polycaprolactone filaments was characterized, and used as input together with the structural parameters of the coupled coils in finite element simulations of tensile loading and three-point bending of the coils. A favorable comparison of the numerical and experimental results was found, which paves way for use of the proposed numerical approach in stiffness design under reversible elastic conditions of filament wound tubular constructs.

1. Introduction

Newborns can display defects in their respiratory, gastrointestinal or genitourinary systems at birth. These defects, such as tracheoesophageal fistula, intestinal atresia, abnormalities of the anus and rectum, some of which are relatively common congenital malformation occurring in 1:3000 to 5000 births (Clark, 1999), may cause diseases that could be fatal. In order to prevent these fatalities, surgeries are needed in order to replace the abnormal segment of tubular organs with patient-specific implants possessing suitable properties. First and foremost, the implants should exhibit a good biocompatibility.

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Second, the implants must also fulfill certain biomechanical characteristics that could be determinant in the proper function of the replaced organ. For example, a change in the geometry and elasticity of cartilage tends to result in tracheomalacia (Lomasney et al., 1989). The mechanical properties of the esophageal smooth muscle are essential to normal deglutition and sphincter competence (Tottrup et al., 1990). Therefore, a full understanding of the mechanical properties of the prototype implants is necessary for designing and manufacturing such solutions. A common design for biological tubular structures and engineering components is helical coils, coupled through a matrix and with a secondary coil that can present a wide range of stiffness and therefore are interesting from a biomechanical design point of view.

In human anatomy and physiology, helical structures are common and observed at different scale levels from nucleotides and bases in DNA up to the adventitia of blood vessels (Holzapfel, 2008; Scarr, 2011), the urinary system, and the intestinal tract (Carey, 1920; Gabella, 1987). Left- and right-handed helical patterns are observed in the epithelium during formation of the esophagus and trachea in the early embryo of pigs (Carey, 1920). Holzapfel (2008) also described the helical collagen reinforcement in the walls of elastic arteries, such as the aorta, which carry high loads from the pressure of blood. Moreover, a helix is fundamental to provide tissue-like compliance while preventing the collapse of tubular structures. Chebli et al., 2012 found that helical winding would promote stabilization of a plant's pollen tube against buckling and collapse during curved growth and compression stress in axial direction. Dotter et al. (1983) developed Nitinol™ wire coils as intra-arterial scaffolds with a high resistance to collapse under external forces.

Motivated by the aforementioned research, we manufactured tubular implants with a coupled helical coil structure, with the eventual aim to be designed as constructs for replacing the abnormal segment of tubular organs in the human body. The material used for manufacturing the implant was polycaprolactone (PCL), which is a resorbable and highly processable biomaterial (Nair and Laurencin, 2007), and widely commercially available. The idea behind using a resorbable biomaterial is to carry external mechanical loads (Williams et al., 2005; Woodruff and Hutmacher, 2010) initially, but allow the progressive degradation and resorption in order to be partially or completely replaced by new tissue (Engelberg and Kohn, 1991; Madeo et al., 2011). To ensure an appropriate bone restoration over the long term, the implant material must have a degradation rate that matches the regeneration rate of new tissues (Domingos et al., 2010). Several studies have focused on the in vivo degradation of polycaprolactone. Lam et al. (2009) conducted in vitro degradation studies of three-dimensional PCL and PCL-based composite scaffolds and the result supported the scaffold design goal for gradual and late molecular weight decreases combined with excellent long-term biocompatibility and regeneration. Domingos et al. (2010) studied the in vivo degradation of PCL scaffold fabricated via bioextrusion, and they concluded that PCL scaffolds have a great potential in tissue engineering, especially in the cases where the scaffold is required to maintain its structure and mechanical properties almost intact for a period of at least 6 months. Moreover, relatively few studies, experimentally or numerically, have been found on the structural behavior of coupled helical coils. Jedwab and Clerc (1993) developed a mathematical model of a self-expanding metallic stent undergoing large deformations but the structure was assumed to be a number of independent open-coiled helical springs whose extremities were hindered to rotate due to the friction between wires in the crossing points. Therefore, realizing the need of a general design approach, our work aims at developing a finite element model for the coupled helical coils with the goal of studying its structural responses at small load conditions. The suitability of the model was verified with data provided by tensile and three-point bending tests. Small irreversible strains are considered, and the sensitivity to the stress–strain relation of the material on the general response of the linear behavior of the structure was small.

2. Materials and methods

2.1. *Preparation of coupled helical coils*

PCL filaments used for manufacturing coupled helical coils were produced from granular PCL (CAPA 6800 Perstorp; M_w=80,000 kDa). As received granular PCL was charged into an extruder with the temperature distribution increasing from 35 °C in the chamber to 123 °C in the nozzle. The extruded PCL filaments had an average diameter of 0.30 mm. The PCL filaments were wound onto a bobbin, then dried under vacuum at room temperature, and kept from humidity and light in a sealed aluminum bag until use.

Coupled helical coils were made at Swerea SICOMP (Piteå, Sweden) using a CNC lathe (Siemens) in combination with a filament winding machine (Waltritsch & Wachter). The manufacturing equipment is shown in Fig. 1(a). The preformed PCL filaments were wound onto a polytetrafluoroethylene-coated needle tube mandrel with an outer diameter of 4.0 mm. To obtain a coupled helix structure, different wound directions (left-handed or right-handed) were used in wrapping the filaments. The right-handed wound filaments had a pitch (i.e., the width of one complete turn, measured along the axis of the helix) of 1.0 mm, and the left-handed wound a pitch of 2.0 mm, while the total length of the coils was 36.0 mm, as shown in Fig. 1(b). The helically asymmetric winding was chosen after systematically trying some different structures to obtain a suitable combination of bending and transverse compliance similar to the targeted tubular organs (see e.g. Roberts et al., 1998; Trabelsi et al., 2010). After the winding steps, the tubes were rotated in the oven at 72 °C for 2.5 min to facilitate the fusion of filaments at the intersections. The quality of the coils was examined initially under magnifying glass and later in a scanning electron microscope (Hitachi TM-1000).

2.2. *Mechanical tests*

The PCL filament and coupled helical coils were stored in a sealed aluminum bag with low relative humidity until mechanical testing to prevent premature degradation. Since only small deformation of the coupled helical coils was considered in the present work, only the elastic properties were characterized from tensile tests of single PCL filaments.