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Research Paper

Tensile behaviour of structurally gradient braided prostheses for anterior cruciate ligaments

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ABSTRACT

Anterior cruciate ligament (ACL) is a key fibrous connective tissue that maintains the stability of a knee joint and it is the most commonly injured ligament of the knee. A synthetic prosthesis in the form of a braided structure can be an attractive alternative to biological grafts provided that the mechanical properties can be tailored to mimic the natural ACL. In the present work, the polypropylene based structurally gradient braided prostheses have been designed and developed by understanding their tensile properties. Circular braiding process was employed to fabricate structurally gradient braided prostheses by systematically placing different types of braids in defined set of layers. An analytical model for predicting the tensile properties of structurally gradient braided prostheses has been presented by modifying and combining the existing models available in the literature. Specifically, the full set of stress–strain behaviour of structurally gradient braided prostheses has been computed based upon braid structural characteristics, constituent strand properties and braid kinematics. A triaxial braid in the outer layer of braided prostheses was found to withstand higher tensile stresses in comparison to a biaxial braid having same structural characteristics. A comparison has been made between the theoretical and experimental results of tensile properties of structurally gradient braided prostheses. The tensile properties of structurally gradient braided prostheses predicted through analytical route matched reasonably well with the experimental results.

1. Introduction

Ligaments are fibrous connective tissues between two or more bones that augment the mechanical stability of joints. Anterior cruciate ligament (ACL) is an intraarticular ligament that controls the kinematics of knee movement and it acts as a joint stabiliser by connecting the femur to the tibia, which is surrounded by synovial fluid (Cooper et al., 2005). ACL can get ruptured during any sport or exercise activity and these injuries are not self-healing which often results in permanent disabilities. Various approaches to reconstruct and replace ACL are primarily based upon biological tissue grafting techniques namely autografts, allografts and synthetic grafts (Kwansa et al., 2010). Autograft surgery uses the tissue from the patient whereas the donor tissue is being used in allograft surgery. Each of these grafting techniques has certain

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disadvantages. For instance, the surgical intervention for obtaining the autograft can often lead to both donor site morbidity and donor site pain whereas allograft surgery carries a high risk of disease transmission. These disadvantages have fuelled the exploration of other alternative repair options for ACL that also includes the use of synthetic prosthesis (Laurencin et al., 1999). In the past, some of the widely used nonbiodegradable polymers for manufacturing of these synthetic prostheses include carbon fibre, polyethylene terephthalate, polytetrafluoroethylene, and polypropylene (Thomas et al., 1987; Fujikawa and Seedhom, 1989; Bolton and Bruchman, 1985; McPherson et al., 1985).

In 1980s, ligament augmentation device (LAD) in the form of polypropylene based braided structures has been used for suturing the prepatellar tissue in order to enhance its tensile properties (Kennedy et al., 1980; Roth et al., 1985). The host tissue sustained during the period of degeneration and weakening, which eventually allowed collagenization. The clinical trials were not satisfactory over the long period of time due to the mismatch between the mechanical properties of host and grafted tissue (Kdolsky et al., 1997). This has led to the development of various types of devices including Leeds-Keio device, polyester strips in the case of Dacron device, Trevira-Hochfest device, Pro-pivot device and Ligament Augmentation and Reconstruction System (LARS) that act as prostheses for ACL (Rading and Peterson, 1995; Andrish and Woods, 1984; Seitz et al., 1998; Tiefenboecka et al., in press). However, the enthusiasm for these devices was drifted away as various complications were reported. One of the main reasons for the poor success rate is that these devices did not provide sufficient mechanical support or reinforcement (Batty et al., 2015). This has caused foreign-body reaction with increased permeability of the ligament to synovial liquid and also, the release of wear particle debris into the knee that caused onset of osteoarthritis (Andrish and Woods, 1984; Claes et al., 1995; Ventura et al., 2010). Nevertheless, the modifications in structural design of these prostheses have yielded successful results without any cases of reactive synovitis or infection of the knee (Lavoie et al., 2000; Nau et al., 2002). Therefore, one of the ways to improve the mechanical properties of braided prostheses is by systematically placing different braided structures in defined set of layers that inevitably leads to 'structurally gradient' materials. Since, braided structures have been extensively used as prostheses for ACL (Guidoin et al., 2000). This is a first attempt to understand and predict the tensile response of structurally gradient braided prostheses that can be potentially tailored for ACL. These structurally gradient braided prostheses essentially consist of combinations of biaxial and triaxial braids placed in predefined layers. Moreover, the analytical modelling route for predicting the tensile properties of structurally gradient braided prostheses has been proposed by modifying and combining the existing models available in the literature. Subsequently, a comparison between the theoretical and experimental results has been made pertaining to the tensile properties of structurally gradient braided prostheses.

2. Theoretical analysis

Circular braiding has been used for fabricating narrow rope-like materials by interlacing diagonally three or more strands of filaments. In a conventional circular braiding machine, the strand carriers rotate along a circular track such that half of the carriers rotate in a clockwise direction while the remaining carriers rotate in the counter-clockwise direction (Potluri et al., 2003). As a result, the two sets of strands are intertwined with each other at a bias angle to the machine axis. The strands in a tubular braid are intertwined in a similar way to that of the interlacements of ribbons formed in the Maypole dance. The prosthesis fabricated through this route can be classified as a biaxial braid which consists of intertwined helical filament strands forming a well-defined weave pattern. Furthermore, a set of axial strands of filaments can also be inserted through the holes present on the circular track to produce a triaxial braid. Therefore, both biaxial and triaxial braids consist of two sets of braider strands but the latter also has additional set of axial strands aligned in the direction of braid axis. Both types of braids have their own merits as triaxial braids can provide high stiffness and strength whereas the biaxial braid can yield higher breaking extension. Therefore, the placement of different types of braided structures in various layers can potentially tailor the tensile properties of ACL braided prostheses. In order to understand the tensile behaviour of structurally gradient braided prostheses, it is necessary to understand their geometrical characteristics, as discussed below. Since, the geometrical or topological characteristics are used as input parameters to predict the tensile properties of structurally and non-structurally gradient braided prostheses.

2.1. Topological characteristics of braided prostheses

Typically, a braided prosthesis consists of braider strands that follow a helically undulated path such that each of the constituent strands passes over and under a given set of strand. These local undulations are the main causes for the differences between helix and braid angles (Saraswat et al., 2014). In general, the braid angle is defined as the angle between the undulated strand and braid axes. It is a key topological parameter of the braid that significantly affects its mechanical properties (Rawal et al., 2015a). A simple mathematical relationship has been formulated between the helix and braid angles, as shown below (Wu et al., 1995).

$$\cos\xi = \left(\frac{D\cot\alpha}{\sqrt{(D+d)^2 + D^2\cot^2\alpha}}\right) \tag{1}$$

where ξ is the braid angle, α is the helix angle, d is the diameter of the undulated strand and D is the diameter of a typical regular braid.

Also, the helix angle of braided prosthesis can be computed based upon the process parameters, as shown below (Potluri et al., 2003).

$$\alpha = \tan^{-1}\left(\frac{\omega_h D}{N_h V}\right) \tag{2}$$