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Technical Note

Topologically controlled tensile behaviour of braided prostheses for anterior cruciate ligaments

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ABSTRACT

Anterior cruciate ligament (ACL) is one of the most susceptible ligaments of the knee that can suffer injury. These ruptured ligaments can be treated through surgical intervention using a braided structure that either acts as a substitute graft in isolation or an augmentation device alongside the biological tissue. Therefore, the main objective of the research work is to present an analytical model for predicting the complete set of tensile properties of braided prosthesis consisting of multifilament strands based upon predefined braid geometry and constituent material properties. The model has also accounted for the kinematical changes under defined loading conditions. The research findings have been confirmed by making a comparison between the theoretical and experimental results. The tensile properties of braided prostheses predicted via analytical route matched reasonably well with the experimental results.

1. Introduction

Anterior cruciate ligament (ACL) controls the kinematics of knee movement as it acts as a linkage between femur and tibia. ACL is one of the most frequently injured ligaments of the knee, which is not self-healing and usually requires surgical intervention (Cooper et al., 2005). Prosthetic replacement of ACL through synthetic grafting can be an attractive alternative because it provides an internal support for the host tissue during its transient stage of weakness and degeneration before regaining its original physiological tensile strength (Kumar and Maffull, 1999).

Kennedy and his colleagues (Kennedy et al., 1980; Roth et al., 1985) have successfully pioneered the synthetic grafting technique by introducing ligament augmentation device (LAD) in the form of polypropylene based braided structure which was sutured to the prepatellar tissue in order to increase its tensile strength. LAD sustained the host tissue during the period of degeneration and weakening, which eventually allowed collagenization. These synthetic grafts exhibited excellent short-term results but the clinical trials carried out over a long period were not found to be satisfactory (Mowbray et al., 1997; Guidoin et al., 2000). This is primarily due to the mismatch between the mechanical properties of host and grafted tissue which has formed the basis for the development of other ACL prosthetic 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) (Rading and Peterson, 1995; Andrish and Woods, 1984; Seitz

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et al., 1998; Tiefenboecka et al., 2015). Some of these devices were not commercially successful as they were not able to provide sufficient mechanical support (Batty et al., 2015).

Nevertheless, the modifications in the structural design of these prostheses have renewed the interest keeping in view that these prostheses are expected to be biocompatible, porous, and exhibit mechanical properties comparable or superior to that of natural ACL (Nau et al., 2002; Lavoie et al., 2000). Further, the success or failure of any synthetic prosthesis is dependent upon three major issues, i.e. material, structure and surgical technique (Duval and Chaput, 1997). The first two issues can be controlled by choosing the polymer which is biocompatible and the structure should be designed in a manner that results in comparable or superior mechanical properties to that of natural ACL. Polyester is amongst the widely used material for synthetic ligaments as it is biocompatible and supports tissue in-growth (Duval and Chaput, 1997; Tilney and Boor, 1975). Furthermore, the stress–strain behaviour of polyester braid is a typical "J-shape" curve that is analogous to that of a natural ACL (Mollica et al., 2006). However, the margin of safety of tensile properties of polyester fibre based braids should be kept high as they are found to be deteriorated over a period of time and under high temperature conditions (37–40 °C) (Ambrosio et al., 1994). Therefore, the main objective of the research work is to propose an analytical model for predicting the full set of tensile properties of braided prostheses by formulating the relationship with topological parameters and constituent material properties. This will help in elucidating the main topological parameters that are responsible for superior mechanical properties of braided prostheses.

2. Theoretical analysis

In this research work, braided prosthesis consists of multi-filament strands that are defined as a yarn consisting of multiple strands of filaments (a fibre of an indefinite or extreme length) (McIntyre and Daniels, 1995). In order to avoid any confusion, it is pertinent to simplify the terminology by calling multifilament strands as 'yarn' and each individual strand of the constituent yarn is referred as a 'fibre'. In a typical regular braided prosthesis, the yarn centreline is assumed to follow an undulated sinusoidal path, as illustrated in Fig. 1a. Hence, the expression of a yarn moving in an undulated sinusoidal path is given by the following equation.

$$y = \frac{d}{2}\sin\left(\frac{\pi x}{2p}\right) \tag{1}$$

where d is the yarn diameter and p is the distance between two consecutive yarns in the direction of their axes.

The crimp angle of the undulated yarn (φ) can be easily computed by differentiating the Eq. (1).

$$\tan\varphi = \left.\frac{dy}{dx}\right|_{x=0} \text{ or } \varphi = \tan^{-1}\left(\frac{d\pi}{4p}\right) \tag{2}$$

The total length of the yarn in the undulation repeat along the direction of its axis in a typical regular braided structure (l) can be calculated similar to that of a diamond braid (Phoenix, 1978),

$$l = \frac{4pE(\sin\varphi)}{\pi\cos\varphi} \tag{3}$$

where $E(k) = \int_0^{\pi/2}\sqrt{1-k^2\sin^2 y}\,dy$

Moreover, the crimp of the undulated yarn (c) can be defined as the excess yarn length in the undulation repeat over the projected length. Hence,

$$c = \frac{l}{2p} - 1 \text{ or } c = \frac{2E(\sin\varphi)}{\pi\cos\varphi} - 1 \tag{4}$$

In the past, the fibre volume fraction (defined as the proportion of volume occupied by the fibres to the total volume of the braid in a unit cell) was found to be a key parameter for predicting the tensile properties of braided structures (Rawal et al., 2012). This is because the braids are porous materials and hence, the fibre volume fraction needs to be considered for predicting their tensile properties. The fibre volume fraction of the unit cell (υ_f) in a typical regular braid (as shown in Fig. 1b and c), is given by,

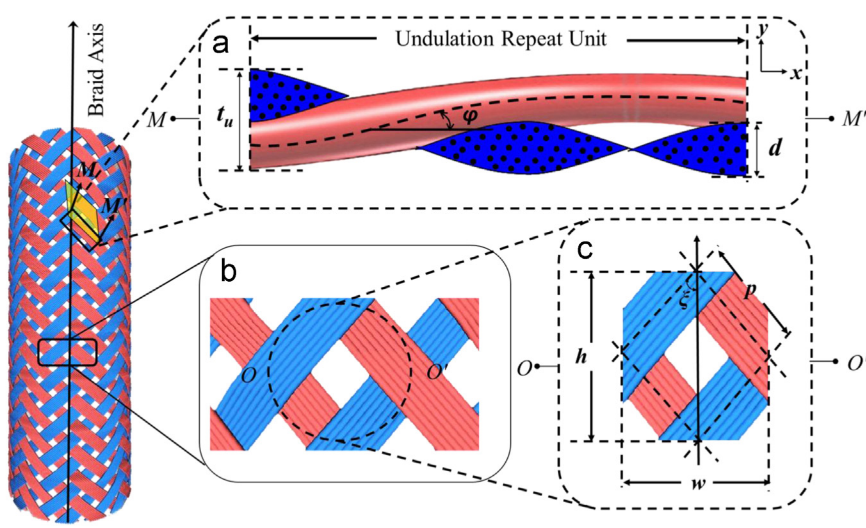

Fig. 1 – Schematic cartoons of regular braided structure consisting of yarns in which magnified image of (a) cross-sectional view of undulation repeat unit, (b) unit cell and (c) diamond trellis is depicted.