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Viscoelastic Behavior of Textile Artificial Ligaments

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Abstract: The main objective of this study is to describe and model viscoelastic behavior of textile anterior cruciate ligament prostheses. For this purpose, mechanical and viscoelastic properties of woven and braided artificial ligaments were studied. These structures were manufactured with the same braided yarn and the same number of yarns. The mechanical properties of the two structures, such as tensile strength, strain at break, work and stiffness were measured by using a constant speed gradient dynamometer. In order to determine the viscoelastic modulus of the two structures, a rheological model was proposed and the correlation between experimental and theoretical creep and relaxation curves were studied. The energy dissipation and the residual deformation were measured with an application developed by using Microsoft Visual Basic software. The obtained results showed that textile structure influences prosthesis viscoelastic and mechanical properties, material damping, hysteresis and residual deformation. The nonlinear viscoelastic model permitted to evaluate the elastic and the viscous modulus of the braided and woven structures and to describe its time-dependent deformation. This study may serve as a method for the selection of the anterior cruciate ligament reconstruction.

Key words: Braid, woven fabric, rheological model, hysteresis, material damping

INTRODUCTION

The Anterior Cruciate Ligament (ACL) shearing at the knee articulation is the most frequent injury of ligaments with more than 100000 ACL reconstructions are performed every year in the United States and some 3000 per year in Sweden (Kostogiannis *et al.*, 2007). The ACL lesion causes knee articulation instability. Artificial ligament can be used in replacement or reinforcement of broken natural ligament. These prostheses can be manufactured from various materials. Biocompatible materials currently used as ACL implants include polyethylene terephtalate (PET) polyester fiber, PTFE fiber, polypropylene and polyacrylonitrile fiber (Jedda *et al.*, 2008; Ben Abdessalem *et al.*, 2005). After cleaning, drying and sterilisation with β-irradations, textile ACL prosthesis can be used to replace natural ligaments (Ben Abdessalem *et al.*, 2005).

According to literature, textile ACL prostheses have not been successful in restoring normal knee stability in all clinical cases. Unsatisfactory outcomes and long-term failure rates vary from 3 to 25% according to the current literature (Kostogiannis *et al.*, 2007; Wong and Yip, 2005; Bach, 2003; Bach *et al.*, 1998). Several factors have been identified leading to prosthesis ACL failure, such as tunnel misplacement, unrecognized concomitant ligament injury, biologic graft incorporation, biomechanical (graft fixation) issues (Bach, 2003), lack of stiffness or elasticity and high incidence of fatigue failure on prosthesis reliability (Ben Abdessalem *et al.*, 2005).

An artificial ACL can be braided, knitted or weaved. In all cases, several yarns are interlaced together inducing numerous contacts between them. When a force is applied to the textile structure, filaments composing yarns undergo an elastic deformation and new rearrangements within yarns occur (Carnaby and Pan, 1989). According to Zhong (1995), fibrous materials deformation is highly nonlinear and shows viscoelastic behavior when compared to other engineered materials such as metals.

In the present research, it is proposed to model time-dependent deformation of textile ACL prostheses. This would permit to understand the influence of textile design (weaved and braided structures) on prosthesis mechanical and viscoelastic properties.

MATERIALS AND METHODS

Samples manufacturing: It is proposed to study the mechanical and viscoelastic properties of two textile structures currently used as ACL prosthesis. Braided and weaved ACL prostheses were fabricated by using the same braided yarn (Fig. 1). This braided yarn was manufactured by using a circular braiding machine LESMO with a 16-carriers arrangement (Fig. 2) and a high tenacity terephtalate polyethylene yarn, having a count of 110 dg km^{-1} (dtex). The take up speed corresponds to a

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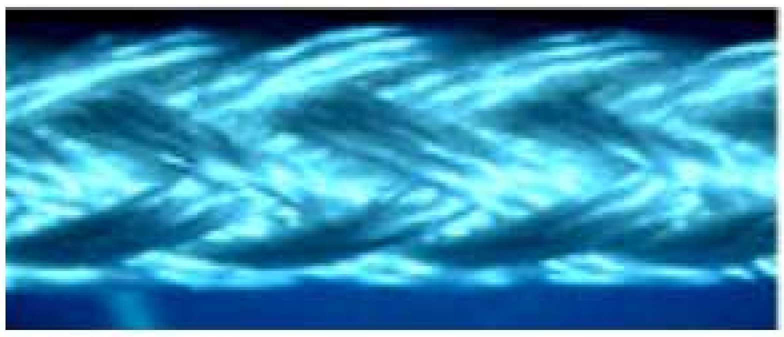

Fig. 1: Circular braided yarn

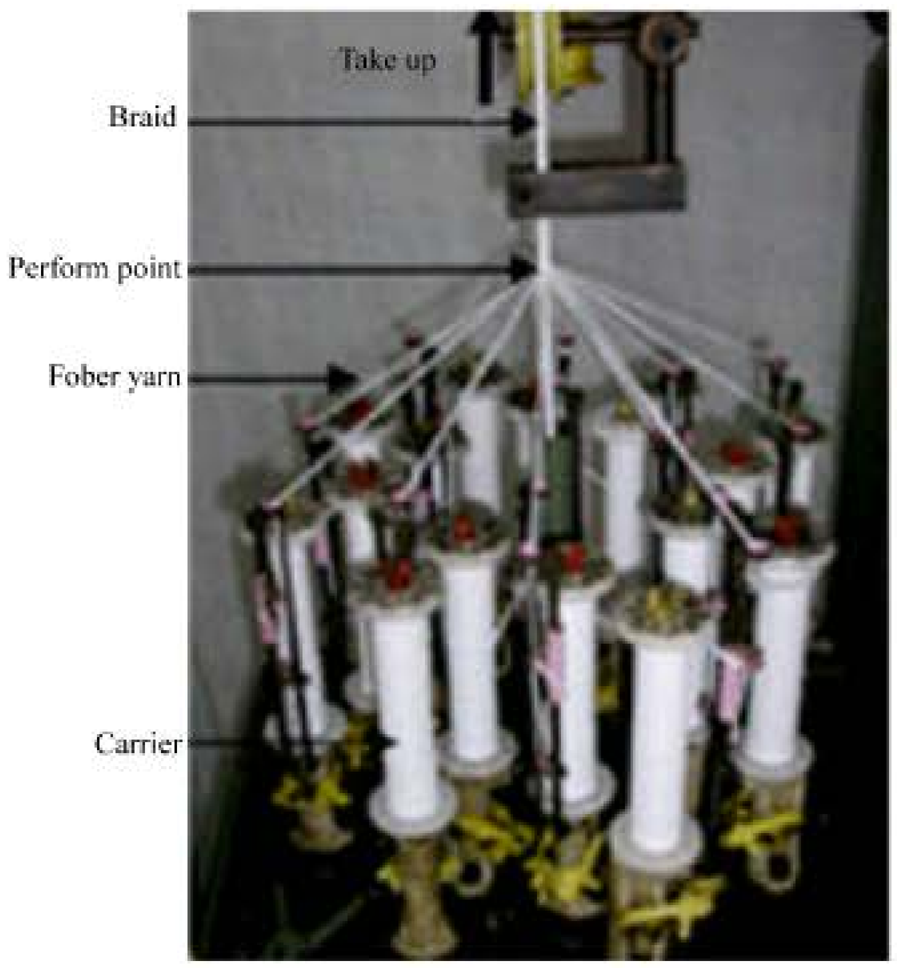

Fig. 2: Circular braiding machine LESMO

cogwheel ratio CR of 1.5. The circular braiding machine has a regular carrier sequential motion (1/1) permitting to interlace the 16 yarns.

The braided yarn (Fig. 1) was used to manufacture a triple core braided structure. The circular braiding machine LESMO interlaces 16 braided yarns and a circular braid is then obtained. The take up speed corresponds to a cogwheel ratio CR of 1.08. In the same circular braiding machine, a central core can be added inside the simple braid. A double braid composed of the 16 braided yarns and having a simple braid as a central core, was braided. Then, a triple braid composed of 16 braided yarns and the double braid as a core, was fabricated (Fig. 3).

A woven ribbon using a shuttle weaving machine (Fig. 4) was also fabricated. This ribbon is composed of 48 braided warp yarns. The warp setting of the woven structure is 10 warps cm^{-1} and the weft setting is 10 wefts cm^{-1}. Then, the woven ribbon is folded and sewed longitudinally in order to obtain a tubular shape (Fig. 5).

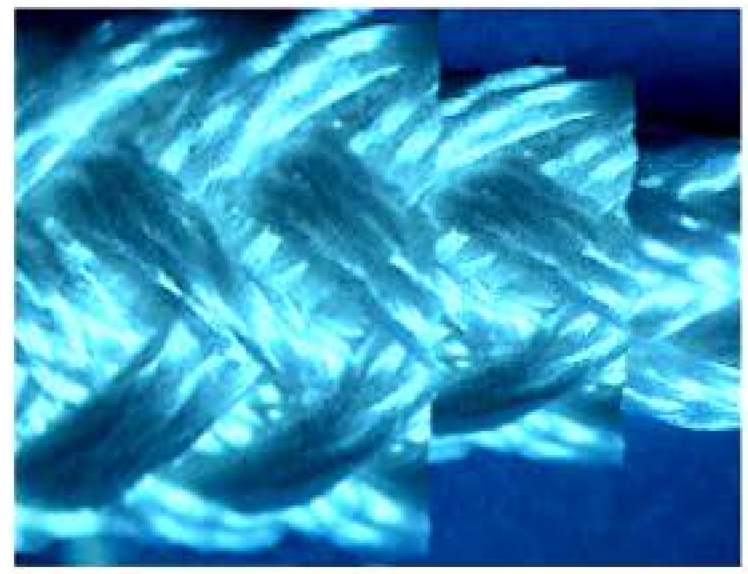

Fig. 3: Triple core-braided structure

Fig. 4: Shuttle weaving machine

Fig. 5: Woven ACL prosthesis

Rheological modelling: Kelvin and Voigt developed a three-element model (Fig. 6) to describe viscoelastic behavior of several materials. The three-element Kelvin-Voigt model is composed of elastic and viscous components. The elastic component was modelled by a spring (E_1) and the viscous component was described by a spring (E_2) and a dashpot (η) connected in parallel arrangement.

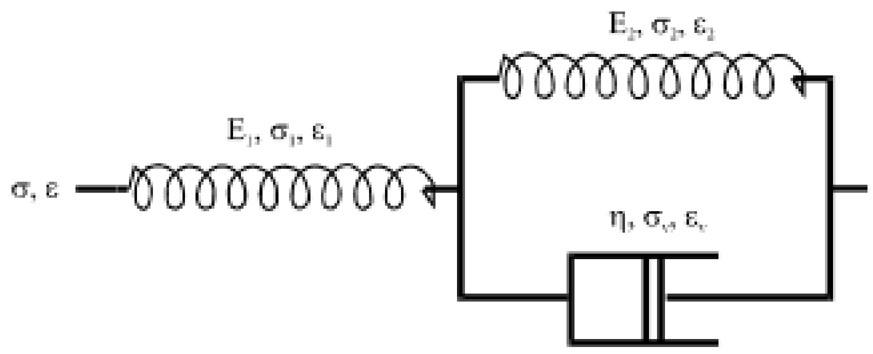

Fig. 6: Kelvin-Voigt model

For the purpose of this study, the nonlinear model was considered because preliminary tests showed that the deformation of woven and braided ACL prostheses under creep and relaxation tests is nonlinear. The nonlinear Kelvin-Voigt model was used to describe the viscoelastic behavior of braided and woven ACL prostheses.

The association of the springs and the dashpot in the three-element Kelvin-Voigt model permitted to consider the following equations:

$$\sigma = \sigma_1 = \sigma_2 + \sigma_v \tag{1}$$

$$\varepsilon_2 = \varepsilon_v = \varepsilon - \frac{\sigma_1}{E_1} \tag{2}$$

$$\sigma_2 = E_2\varepsilon_2 = E_2(\varepsilon - \frac{\sigma}{E_1}) \tag{3}$$

$$\sigma_v = \eta\frac{\partial\varepsilon_v}{\partial t} = \eta\frac{\partial}{\partial t}(\varepsilon - \frac{\sigma}{E_1}) \tag{4}$$

where, σ is stress and ε is strain.

According to Eq. 1-4, we have:

$$\sigma = (E_2\varepsilon - \frac{E_2}{E_1}\sigma) + (\eta\frac{\partial\varepsilon}{\partial t} - \frac{\eta}{E_1}\frac{\partial\sigma}{\partial t}) \tag{5}$$

Finally, Eq. 6 governs stress-strain behavior of three-elements Kelvin-Voigt model:

$$\sigma(1 + \frac{E_2}{E_1}) + \frac{\eta}{E_1}\frac{\partial\sigma}{\partial t} = E_2\varepsilon + \eta\frac{\partial\varepsilon}{\partial t} \tag{6}$$

In a creep test, stress applied to material remains constant and deformation changes during time. In order to describe creep behavior of braided structure with three-element Kelvin-Voigt model, Eq. 6 was integrated. Strain dependence on time under constant stress σ_0 is given by Eq. 7:

$$\varepsilon(t) = \frac{\sigma_0}{E_{12}}\left[1 + \frac{E_1}{E_2}\left\{1 - \exp(-\frac{t}{\tau})\right\}\right] \tag{7}$$

Where:

$$E_{12} = \frac{E_1E_2}{E_1 + E_2} \text{ and } \tau = \frac{\eta}{E_2}$$

The slope (S_c) of the tangent to the creep curve at point (0, σ_0) is given by Eq. 8.

$$S_c = \sigma_0 (E_1 + E_2)/\eta E_2 \tag{8}$$

Relaxation test is a current complementary test of creep test. It permits to measure sample elongation when applied stress decreases with time. In order to describe braided prosthesis relaxation, Eq. 6 can be written:

$$\sigma + t_r\frac{\partial\sigma}{\partial t} = E_{12}\varepsilon + E_1t_r\frac{\partial\varepsilon}{\partial t} \tag{9}$$

Where:

$$t_r = \frac{\eta}{E_1 + E_2}$$

The dependence of stress on time under constant strain ε_0 is given by Eq. 10:

$$\sigma(t) = \frac{E_1\varepsilon_0}{E_1 + E_2}\left\{E_2 + E_1\exp(-\frac{t}{t_r})\right\} \tag{10}$$

The slope (S_r) of the tangent to the relaxation curve at the point (ε_0, 0) is then given by Eq. 11:

$$S_r = \varepsilon_0(E_1^2/\eta) \tag{11}$$

Hysteresis characterization: During cyclic loading-unloading test, viscoelastic material behavior induces a hysteresis phenomenon described by stress-strain diagram (Renz *et al*., 1988). The variation of the hysteresis-loop with material can be described by numerical methods (Fig. 7). The hysteresis-loop shape, the energy dissipation and the residual deformation have a big interest for material characterization. In order to determine material damping, the following procedure was considered in this study:

- The dissipated energy due to viscoelastic material deformation corresponds to the area of the hysteresis-loop obtained during one cycle. This area is determined by numerical integration and called energy dissipation
- The area situated between elongation axis and load-elongation curve corresponds to strain energy in material during one cycle. This area is determined by numerical integration and called total energy

- According to Renz (1988), the relation between energy dissipation and total energy is called material damping (d) and can be calculated according to Eq. 12:

$$d = \frac{\text{Energy dissipation (Nm)}}{\text{Total energy (Nm)}} \tag{12}$$

- After hysteresis test, the ACL prosthesis does not generally recover its initial dimensions. The difference between total extension and plastic deformation is called residual deformation (δ)

Methodology: The mechanical properties of the two structures were measured by using a constant speed gradient dynamometer LRX2.5K Lloyd. Sample is grabbed by dynamometer clamps and undergoes a longitudinal traction till rupture. At breaking instant, tensile strength, strain at break, work and stiffness were registered. Mean tensile strength, mean strain at break, mean work and mean stiffness were calculated (AFNOR, 1985).

In order to examine the proposed rheological model reliability, the rheological model parameters were determined from experimental data and the correlation between experimental and theoretical creep and relaxation curves was studied.

For creep and relaxation tests, a constant speed gradient dynamometer LRX2.5K Lloyd was used. In order to calculate total energy, energy dissipation and residual deformation, the hysteresis curve were processed with an application developed by using Microsoft Visual Basic software (Fig. 7).

Hysteresis and relaxation tests were performed at constant extension of 2.8 mm corresponding to medium elongation of natural ACL during knee motion (Yahia, 1997). Creep test was performed with a constant load corresponding 2.8 mm elongation of the tested sample. Braided and weaved samples were 40 mm long and had a 6 mm diameter.

RESULTS

Mechanical properties of braided and weaved prostheses were obtained from load-extension tests. Mechanical properties of the natural ACL were investigated by Woo *et al*. (1991). These properties were compared to those of the developed prostheses (Table 1). Table 1 shows that material damping and residual deformation of woven structure are lower than those of braided structure. Table 1 and Fig. 8 show that braided and woven structures have higher strength and stiffness than natural ACL. In the other hand, woven structure and braided structure showed different mechanical performances. In fact, load at break and stiffness of the woven structure are higher than those of braided structure and natural ACL. Extension and work corresponding to woven structure are lower than those of braided structure and natural ACL. It can clearly seen that, braided structure presented mechanical performances close to those of natural ACL. Indeed, it was report in literature that for natural ACL, ultimate tensile load is situated around 2000 N, stiffness is between 129-182 N mm^{-1}, work at break is situated around 14.96 N.m and strain at break is about 15 mm (Yahia, 1997).

Table 1: Mechanical properties of natural and artificial ACL

Properties	Woven ACL	Core braided ACL	Natural ACL
Tensile strength (N)	2450	2046	2109
Strain at break (mm)	7.5	11.3	14.95
Stiffness (N mm^{-1})	326	181	176
Work at break (Nm)	9.11	11.6	14.96
Total energy (Nm)	1.08	0.79	-
Material damping	0.45	0.52	-
Residual deformation (mm)	0.90	1.14	-

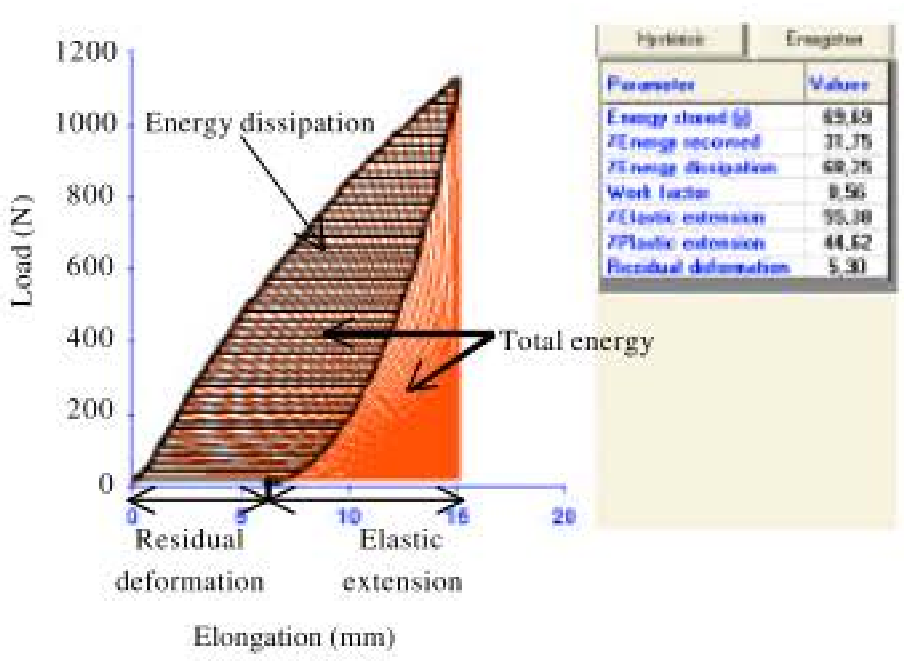

Fig. 7: Numerical method of hysteresis measurement

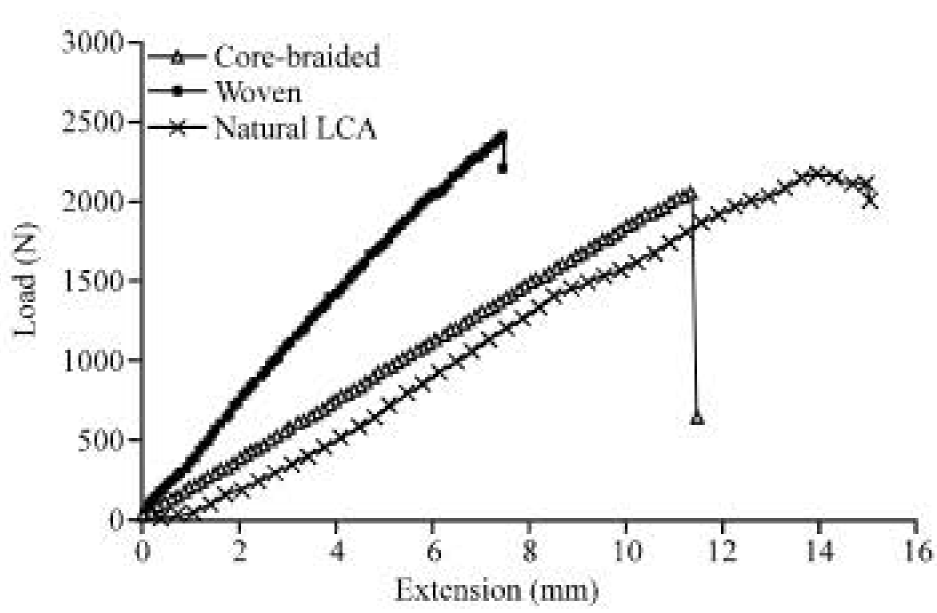

Fig. 8: Effect of textile design on mechanical ACL prosthesis properties

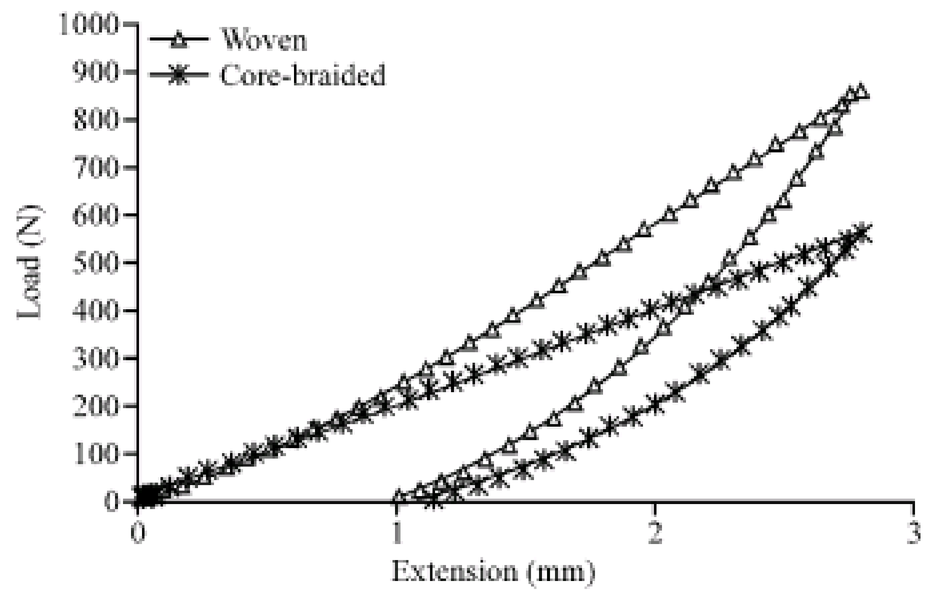

Fig. 9: Effect of textile design on hysteresis loop shape

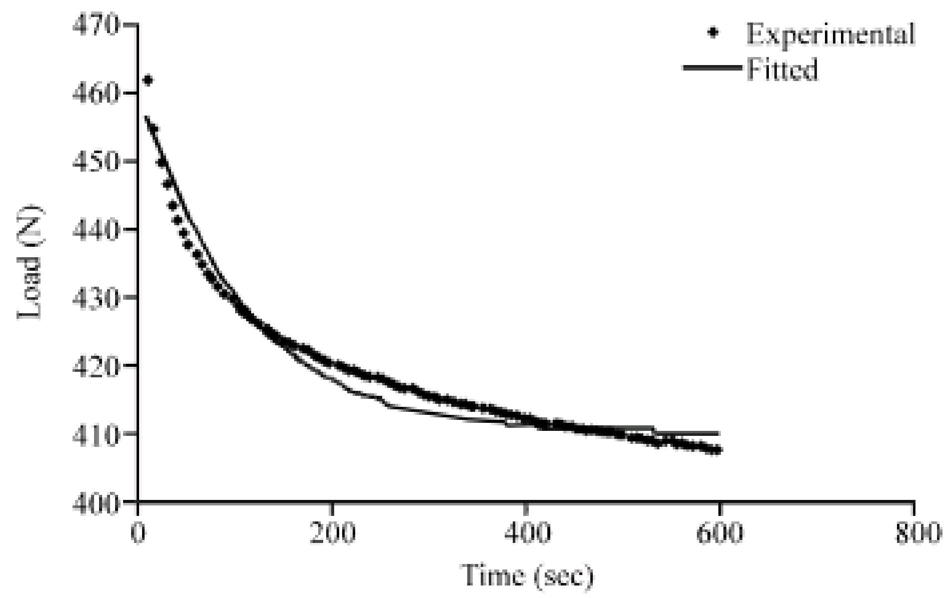

Fig. 10: Experimental and non linear fitted relaxation curves of braided ACL prosthesis

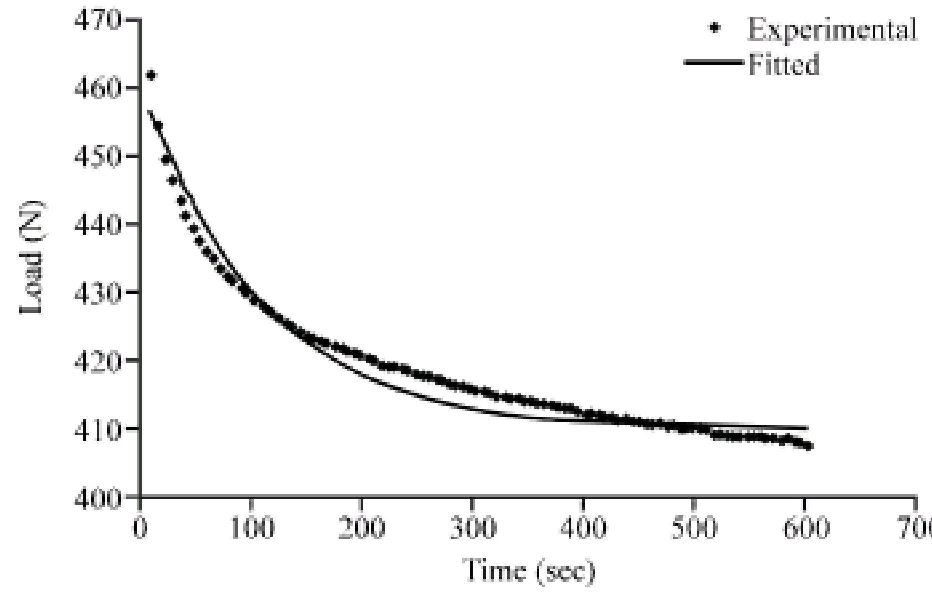

Fig. 11: Experimental and non linear fitted relaxation curves of woven ACL prosthesis

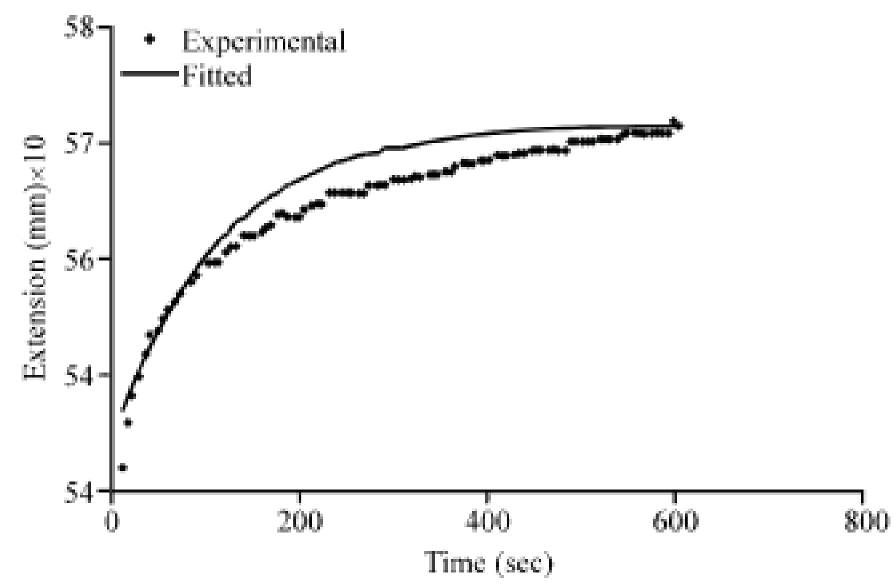

Fig. 12: Non linear fitted creep curve of braided prosthesis ACL

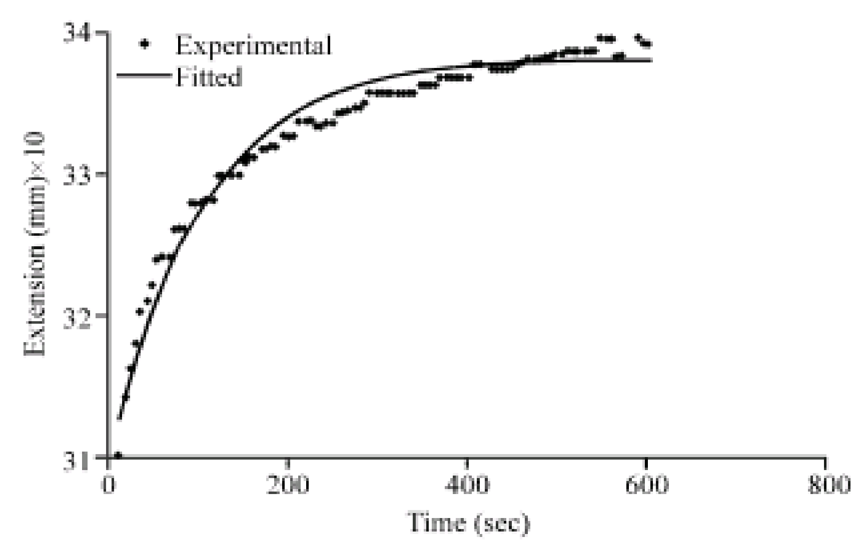

Fig. 13: Non linear fitted creep curve of woven prosthesis ACL

Figure 9 shows that unloading path of load-extension curve is different from loading portion. This behavior called hysteresis effect is linked to energy dissipation during test. It's clearly that the hysteresis-loop of woven structure is different from that of braided structure. This shows that prosthesis textile design influences hysteresis curves shape.

In order to test the proposed rheological model during creep and relaxation test, the correlation between theoretical and experimental data was studied. For this purpose, experimental elongation was compared with fitted elongation by using Origin 6.0 software. Figure 10 and 11 show, respectively experimental and calculated relaxation curves for woven and braided ACL prostheses. Figure 12 and 13 show experimental and calculated creep curves for woven and braided ACL prostheses, respectively. The nonlinear Kelvin-Voigt model seems to be adequate to describe creep and relaxation behavior of the woven and braided ACL prostheses. In fact, correlation coefficient R^2 exceeds 95%. The calculated parameters of the rheological model related to relaxation and creep test were summarized in Table 2 and 3.

Table 2: Kelvin-Voigt model parameters related to relaxation test

Parameters	Woven ACL	Core-braided ACL
E_1 (N mm^{-1})	275	165
E_2 (N mm^{-1})	2389	1298
η (N mm^{-1})	266307	157181
S_r (N sec^{-1})	0.793	0.486

Table 3: Kelvin-Voigt model parameters related to creep test

Parameters	Woven ACL	Core-braided ACL
E_1 (N mm^{-1})	364	103
E_2 (N mm^{-1})	3898	2025
η (N mm^{-1})	38561	232164
S_c (mm sec^{-1})	0.0292	0.00241

DISCUSSION

Hysteresis curve allows to determine energy dissipation due to friction between filaments after loading. Friction due to cohesion between filaments is opposed to return of filaments to their original arrangement after traction. Linear textile deformation is associated to elastic deformation and also to rearrangement of yarns. According to Zhong (1995), who studied the deformation behavior of braided fiber seals by using nonlinear viscoelastic model, when the elastic deformation is dominant in total deformation of braided fiber, the dimensional recovery is significant. In this case, as shown in Fig. 9, residual deformation of woven structure is about 0.9 mm and residual deformation of the braided structure is about 1.14 mm. This can be explained by the fact that elastic deformation is higher for woven structure.

The presence of residual deformation and two different paths for loading and unloading implies that developed prostheses ligament present a viscoelastic behavior. Brusselle (2002), who characterized and modelled the uniaxial mechanical behavior of polypropylene filament, showed that the difference between loading and unloading paths of polypropylene filaments is affected by material viscosity. The three-element Kelvin-Voigt model permitted to study the viscoelastic behavior of the manufactured ACL prostheses. This model includes material elasticity represented by a spring (E_1) and material viscosity represented by a spring (E_2) and a dashpot (η).

The proposed rheological model permitted to determine viscoelastic contribution to creep and relaxation response of manufactured prostheses. According to the Table 2 and 3, parameters S_r and S_c , which depend on the viscoelastic modulus, of woven structure are more important than those of core-braided structure. For woven structure, S_r is higher than for braided structure. This indicates that stress relaxation for woven ACL decreases more rapidly with time than for braided ACL. During creep test, high S_c value of woven structure indicates that for this structure, deformation increases more rapidly than in the case of braided structure. S_c gives also an idea about structure stiffness. Figure 9, 10 and Table 1 show clearly that woven ACL stiffness is more important than that of core braided structure. Parameter S_r gives an idea about structure recovery speed, material damping and residual deformation. In fact, when S_r increases, material damping and residual deformation decreases. These results are in agreement with the hysteresis test. In fact, woven structure represents lower material damping and lower residual deformation because recovery of this structure is quicker than for braided structure.

CONCLUSIONS

This study investigated the influence of textile artificial ligament design on its mechanical and viscoelastic properties in the case of braided and woven structures manufactured from braided terephtalate polyethylene yarn. The woven structure showed higher mechanical performances but the braided structure presented mechanical performances closer to those of the natural ACL.

The use of the proposed nonlinear rheological model permitted to investigate the viscoelatic behavior of the ACL prostheses. Elastic and viscous modulus, were obtained from the relaxation and creep test and nonlinear viscoelastic model permitted to describe time-dependent deformation of the studied ACL prostheses.

Material damping and residual deformation of woven structure are lower than those of braided structure which seems to be mechanically more suitable to be used as artificial ACL, but woven structure is more likely to recover its original length rapidly.

Further work will focus on *in vitro* comparison between mechanical performances of woven and braided structures by using a fatigue tester that simulates simultaneous bending, traction, twist and abrasion constraints applied to ACL during knee motion.

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