Time-dependent behaviour of native ligament and synthetic grafts used in ACL reconstruction

M. Zingales[1], G. Marchiori[2], E. Bologna[1], D. Spadaro[1], L. Camarda[3], M. Berni[2], N.F. Lopomo[2,4]
[1] *DICAM, University of Palermo, Italy; email: massimiliano.zingales@unipa.it*
[2] *Laboratory of Biomechanics, Rizzoli Orthopaedic Institute, Italy; gregorio.marchiori@ior.it*
[3] *DISCOG, University of Palermo, Italy; email: lawrence.camarda@unipa.it*
[4]*DII, University of Brescia, Italy; email: nicola.lopomo@unibs.it*

Abstract **— Concerning Anterior Cruciate Ligament (ACL), an overall characterization of native and synthetic specimens, used during reconstruction, is still lacking, above all focusing on their time-dependent behaviour. The main goal of this work was to implement a complete testing protocol able both to investigate pre-implant mechanical characteristics and to provide useful data for visco-elastic material modelling.**

Keywords **— ACL; synthetic; stress-relaxation; creep**

I. INTRODUCTION

Anterior Cruciate Ligament (ACL) is one of the major ligaments of the knee joint and, for its prominent functional role, is highly susceptible to injury. In the last decade, during ACL reconstruction, synthetic grafts have been increasingly proposed to (fully or partially) substitute a torn ACL. Ideally, these grafts should mimic the native ligament mechanical behavior but, in the clinical practice, they may still present poor functional outcomes, altering the knee biomechanics. Fundamental issues related to synthetic grafts are their sub-optimal mechanical properties [1], a still incomplete biomechanical characterization [2] and the impossibility to reliably predict their behaviour within the knee joint. This study aimed to mechanically test, model and compare native ACL and polyethylene terephtalate synthetic ligament (S). The characterization was focused on time-dependent behavior, including stress-relaxation and creep phenomena, which play a critical role in the physiological function of the knee [3] and are inherently related to ligaments/grafts peculiar microstructure. Data were collected in order to: 1) reveal if the rate of stress-relaxation/creep is strain/stress dependent; 2) perform a comparison between native and synthetic ligaments in terms of visco-elastic behaviour; 3) reveal a possible interrelation between relaxation and creep phenomena.

II. MATERIALS AND METHODS

A specific protocol (thawing; preconditioning; 100 s stress-relaxation; 100 s creep; 15 min pause to recover. Figure 1) was designed, implemented by using a dynamic single-axis test system (Bose 3330, TA instruments) and applied on six specimens of native ACL and polyethylene terephtalate synthetic ligament (S). Specifically, ligament strain values as identified in common activities [5] were imposed (1, 2, 3, 4, 5%) and maintained, for relaxation testing; once recovered, samples underwent creep at the maximum load, as reached in the previous relaxation phase.

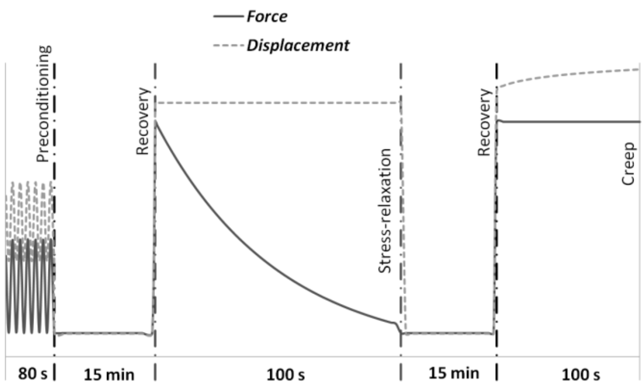

Figure 1. Scheme of the testing protocol, where “Force” is the vertical force read by the load cell (Newton) and “Displacement” is the distance between clamps (millimetres)

Stress-relaxation and creep curves were modelled by assuming a power law model [6], specifically stress σ at time t during the constant deformation phase is

$$\sigma(t) = At^{-\beta} \quad (1)$$

and strain ε at time t in the constant load phase is

$$\varepsilon(t) = Bt^{\beta} \quad (2)$$

where t is expressed in seconds and β is the rate of relaxation or creep.

On other specimens of ACL and S, monotonic stress-strain curves were collected in order to highlight the response in the investigated 1-5% deformation range.

Rate β was compared: between different strain/stress levels inside the same samples group (ACL and S); between ACL and S, both for stress-relaxation and creep; between stress-relaxation and creep inside the same samples group (ACL and S).

The Kruskal-Wallis test was employed (p-value = 0.05) for the analysis. If a significant difference was observed, multiple comparisons were than performed by using Wilcoxon ranksum test with a level of statistical significance p-value = 0.05.

II. RESULTS

No significant differences were found between stress-relaxation/creep rates β at different strain/stress levels (e.g. for ACL, Figure 2).

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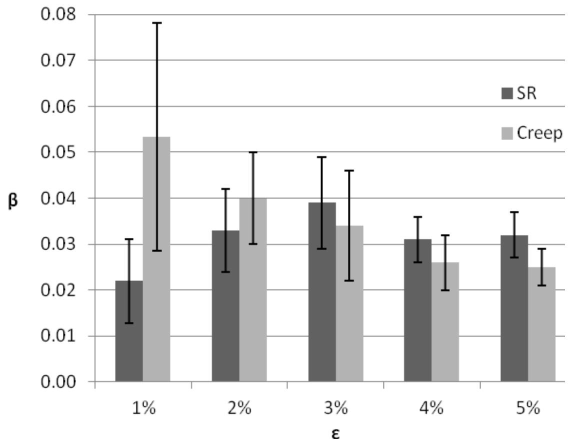

Fugure 2. Stress-relaxation (SR) and creep (Creep) rate β at the various strain levels 1-2-3-4-5% for ACL group.

Monotonic stress-strain curves supported this finding, showing a linear trend in the response on the investigated deformation range, both for ACL and S (Figure 3).

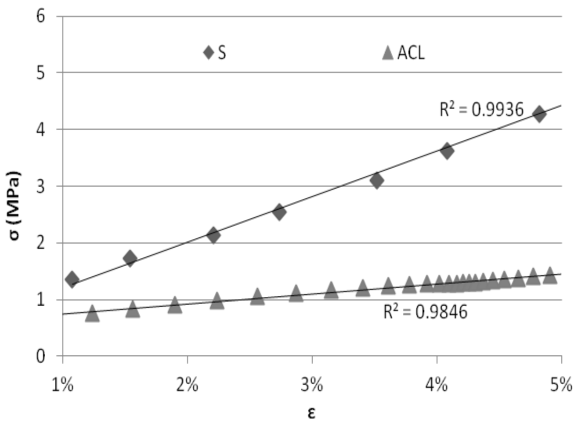

Figure 3. Monotonic curves in the 1-5% strain range. Imposed linear fitting was good: relative coefficient of determination R^2 is closed to 1.

ACL relaxes more slowly, whereas S creeps much faster. These results underlined that the initial higher stiffness of the synthetic ligament respect to the native one may be balanced over time. Furthermore, stress relaxation proceeded faster than creep: the linear visco-elasticity with an exponential law was not met.

III. Discussion

For the first time in a single study, both native ACL and the most commonly used synthetic grafts were tested under stress-relaxation and creep conditions, by considering different levels of strain/stress, with the aim of – first - comparing the time-dependent behavior of the two different materials and – secondary - trying to correlate the two phenomena from a phenomenological point of view.

In this study, the two possible sources of nonlinearity in the viscous mechanical response were represented by the influence of the stress level in its temporal evolution and by different time-dependent dynamics between stress-relaxation and creep. From a modeling point of view, the first influencing factor translates into the impossibility to separate the involved variables (time and strain/stress), the second in the necessity of describing stress-relaxation and creep phenomena considering different parameters.

The results of this study highlighted how different levels of strain/stress did not influence the time-dependent behavior of the ligaments and grafts, confirming what already reported for native ACL [6] considering the only stress-relaxation phenomenon. However, the reported findings underlined significant differences between the time-dependent behavior of the two considered materials. Furthermore, differences between stress-relaxation and creep phenomena were reported for both native ligament and synthetic grafts; conditions that, until now, were demonstrated only on animal tissue [7].

IV. Conclusion

This study reported interesting findings concerning the time-dependent behavior of native ACL and synthetic grafts. Furthermore, here is reported a first preliminary attempt to model stress-relaxation and creep, in a perspective of predicting graft behavior. About these findings, two possible solutions could be pursued to model together stress-relaxation and creep phenomena in native and synthetic ACL: trying to adapt the linear visco-elastic theory to the micro-structure of the analyzed tissues, or introducing a more complete description that takes into account the fluid phase among the fibers of the tissue.

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