**viscoelastic modeling of porcine ligaments**

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**Abstract.** Viscoelastic quasi-linear analytical models, as Fung, was implemented through the utilization of experimental results obtained from several porcine ligaments as: lateral collateral ligament (LCL), anterior cruciate ligament (ACL), posterior cruciate ligament (PCL) and medial collateral ligament (MCL). To implement quasi-linear viscoelastic models for soft tissues, as the Fung one, was necessary the utilization of a programming language, as C Sharp, and Object-oriented programming to deal with the model’s mathematical demands, as the convolution calculations. Moreover, those technologies allow to reduce the code execution time which was one of the main problems. Despite this benefit, was necessary to implement the numerical methods used in process. The models’ results show the stress evolution in relaxation tests. Although The preliminary results show a good correlation between experimental and analytical models, showing a noticeable change in ligaments stiffness after the experimental implementation of relaxation tests.

**Keywords:** knee ligaments, analytic model, viscoelasticity, Fung

1. Introduction

The purpose of these paper is to explain how to implement quasi-linear viscoelastic models for soft tissues. For that, it is necessary the utilization of a programming language to deal with the model’s mathematical demands, as the convolution, integral and derivative calculations, and with the complex logics to be dealt with. In that research, is used C Sharp as

1. Text format

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The manuscripts should be written in English, typed in A4 size pages, using font Times New Roman, size 10, except for the title, authors affiliation, abstract and keywords, for which particular formatting instructions are indicated above. Single space between lines is to be used throughout the text.

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All the symbols and notation must be defined in the text. Physical quantities must be expressed in the SI (metric) units. Mathematical symbols appearing in the text must be typed in *italic* style. Units must be typed in roman style (e.g., kg, m, MJ, kW/m2, instead of *kg*, *m*, *MJ*, *kW/m2*).

Bibliographic references should be cited in the text by giving the last name of the author(s) and the year of publication, according to the following examples: “Recent work (Simas and Di Gregorio, 2019), …” or “Recently, Simas and Di Gregorio (2019), …”. In the case of three or more authors, the form “(Bravo *et al.*, 2018)” should be used. Two or more references having the same authors and publication year must be distinguished by appending “a”, “b”, etc., to the year of publication. For example: “In the works of Santos *et al*. (2013a) and Santos *et al*. (2013b), …”.

Acceptable references include journal articles (Bravo *et al.,* 2018), articles published in conference proceedings (Santos *et al.*, 2013a, 2013b), conference proceedings (Carvalho, 2017), books (Mendonça and Fancello, 2019), Master’s Theses (Campos, 2018) and Doctoral Dissertations or Doctoral Theses (Grando, 2017), patents (Fernandes et al., 2018), reports, when publicly available, (EPE, 2020), websites and specific pages in websites (MLA, 2020), and submitted articles (if the journal is identified).

References should be listed at the end of the manuscript according to instructions provided in Section 4.

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* 1. Section titles and subtitles

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The section headers and sub headers must be aligned at left, typed with Times New Roman, size 10, bold style font. They must be numbered using Arabic numerals separated by points. No more than 3 sublevels should be used. One single line size 10 must be included above and below each section title/subtitle.

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The mathematical equations must be indented by 0.5 cm from the left margin. They must be typed using Times New Roman (or Cambria Math), *italic*, size 10 pt. font. Arabic numerals must be used as equation numbers, enclosed between parentheses, right-aligned, as shown in the example below. Equations should be referred to either as “Eq. (1)” in the middle of a phrase or as “Equation (1)” in the beginning of a sentence. Matrix and vector quantities can be indicated either by brackets and braces, as in Eq. (1), or in bold style, as in Eq. (2). One blank line must be included above and below each equation. Symbols used in the equations must be defined immediately before or after their first appearance.

“The equation of the dynamical system is written in one of the two forms,

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|  |  |
| --- | --- |
| , | (1) |

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or,

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| --- | --- |
| , | (2) |

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where or , or, and orare the mass, dissipation, and stiffness matrices, respectively, and or , or , or , and or are the acceleration, velocity, displacement and input force vectors, respectively.”

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* 1. Figures and tables

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Figures and tables should be placed in the text as close as possible to the point they are first mentioned and must be numbered consecutively in Arabic numerals. Figures must be referred to either as “Figure 1” in the middle of a phrase or as “Figure 1” in the beginning of a sentence.

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Figure 1. Schematic diagram of the control strategy.

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The figures, as well as their captions, must be centered in the breadth-wise direction. The captions of the figures should not be longer than 3 lines, centered and in Times New Roman size 10.

One blank line must be left before and after each figure.

The legend for the data symbols as well as the labels for each curve should be included into the figure. Lettering should be large enough for ease reading. All units must be expressed in the S.I. (metric) system.

Color figures and high-quality photographs can be included in the manuscript. To reduce the file size and preserve the graphic resolution, figures must be saved into GIF (figures with less than 16 colors) or JPEG (for higher color density) files before being inserted in the manuscript.

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One blank line must be left before and after each table.

The style of table borders is left free. An example is given in Table 1.

Cross references for equations, figures and tables are used in this template. The corresponding labels are Equation, Figure, and Table, respectively.

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Table 1. Experimental results for flexural properties of CFRC-4HS and CFRC-TWILL composites.

Span/depth ratio = 35:1. Average results of 7 specimens.

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|  |  |  |
| --- | --- | --- |
| **Composite Properties** | **CFRC-TWILL** | **CFRC-4HS** |
| Flexural Strength, MPa(1) | 209 ± 10 | 180 ± 15 |
| Flexural Modulus, GPa(1) | 57.0 ± 2.8 | 18.0 ± 1.3 |
| Mid-span deflection at the failure stress, mm | 2.15 ± 1.90 | 6.40 ± 0.25 |

(1) measured at 25°C

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1. Acknowledgements

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This optional section must be placed before the list of references.

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1. References

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Campos, R., 2018. Design of quick couplings for drones and moving vehicles (in Portuguese). Master’s Thesis, Graduate Program in Mechanical Engineering, Federal University of Santa Catarina, Florianópolis, Brazil.

Carvalho, J.C.M., Martins, D., Simoni, R., and Simas, H., 2017. Multibody Mechatronic Systems - Proceedings of the MUSME Conference held in Florianópolis, Brazil, October 24-28, 2017. Mechanisms and Machine Science. Springer International Publishing.

EPE, 2020, *Brazilian Energy Balance 2020*, *Final Report* (in Portuguese), Empresa de Pesquisa Energética EPE, Rio de Janeiro, epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-479/topico-528/BEN2020\_sp.pdf. Accessed 12 January 2021.

Fernandes, R.B., Teixeira, J.S.V., Boeing, F., Pedro Filho, A., Berramashi, E.A., Tounier, M.B., Silva, M.B., and Caminha Junior, L., 2018. “System for monitoring controlled areas in work environments (in Portuguese)”. Patent, INPI - Instituto Nacional da Propriedade Industrial, Brazil, Utility Model, Registry number: BR10201806780403, Deposit: September 04, 2018.

Grando, M.T., 2017. Complacency of cable guided robotic systems (in Portuguese). Doctoral Dissertation, Graduate Program in Mechanical Engineering, Federal University of Santa Catarina, Florianópolis, Brazil.

Mendonça, P.T.R. and Fancello, E.A., 2019. The method of finite elements applied to mechanics of solids (in Portuguese). Editora Orsa Maggiore, Florianópolis.

MLA, 2020. *MLA works cited: Electronic sources (web publications)*. Modern Language Association, Purdue Online Writing Laboratory, Purdue University, https://owl.purdue.edu/owl/research\_and\_citation/mla\_style/mla\_formatting\_and\_style\_guide/mla\_works\_cited\_electronic\_sources.html. Accessed 12 January 2021.

Santos, D.D., Furtado, G.M., Frey, S.L., Naccache, M.F., and de Souza Mendes, P.R., 2013a. “Flow of elasto-viscoplastic fluids inside a cavity”. In Proceedings of the 22nd International Congress of Mechanical Engineering - COBEM 2013. Ribeirão Preto, Brazil.

Santos, D.D., Furtado, G.M., Frey, S.L., Naccache, M.F., and de Souza Mendes, P.R., 2013b. “Numerical investigation of elastic and viscous effects on inertial viscoplastic fluid flows”. In Proceedings of the 22nd International Congress of Mechanical Engineering - COBEM 2013. Ribeirão Preto, Brazil.

Simas, H. and Di Gregorio, R., 2019. “A technique based on adaptive extended jacobians for improving the robustness of the inverse numerical kinematics of redundant robots”. Journal of Mechanisms and Robotics, Vol. 11, p. 020913.

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