11º CONGRESSO NACIONAL DE BIOMECÂNICA
A. P. G. Castro, C. Pina, P. R. Fernandes, C. Santos, J. Folgado & A. Amaro (Eds)
Sesimbra, Portugal, 21-22 de Fevereiro, 2025

Development of a nonlinear Torsional Spring for Exoskeleton Actuation

***Maria Fonseca*[1], *Sérgio B. Gonçalves*[1], *Luís Quinto*[1,2] *and Miguel Tavares da Silva*[1]**

[1] IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, Lisboa 1049-001, Portugal

[2] CINAMIL, Academia Militar, Portugal

{maria.r.v.fonseca, sergio.goncalves, miguelsilva}@tecnico.ulisboa.pt,

luis.quinto@academiamilitar.pt

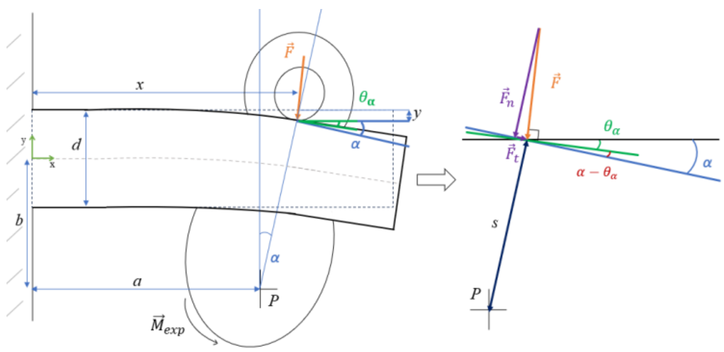
Keywords: Torsional Spring, Nonlinear Actuation, Passive and Quasi-passive Actuation, Ankle Exoskeleton, Dual-use Exoskeleton

1 Introduction

Exoskeletons supporting locomotion represent a rapidly growing field of research driven by technological advancements and their wide range of applications in industry, rehabilitation, and mobility assistance. The ankle joint is often prioritized in such designs due to its role in generating the highest torques during gait [1]. Nevertheless, achieving a natural biomechanical response through a nonlinear relationship between ankle kinematics and actuator torque remains a key challenge [2]. Passive and quasi-passive exoskeletons require the introduction of mechanical elements capable of producing nonlinear responses. Building on the work of [3], this project aims to develop a nonlinear torsional spring that better approximates the natural ankle angle-torque relationship. The proposed element is intended for integration into the quasi-passive ankle exoskeleton, Elite II, which aims to reduce the locomotion's metabolic cost for both military and civilian applications [4].

2 Analytical model

The spring's mechanism of operation is based on the deformation of a beam by an external force. The difference between the actuator's rotation angle (α) and the beam's deformation angle (θ) creates a nonlinear reaction moment, while within the material's elastic domain. Figure 1 schematically shows this deformation, with (a,b) representing the xy coordinates of the actuator's fixed point P, d as the height of the beam, c (not shown) as its depth, x as the coordinate of the force application point and s as the distance between P and the force application point.



(a) *(b)*

Figure 1 – (a) Schematic representation of the torsional spring; (b) Corresponding force diagram.

The proposed model is based on the equations for the calculation of the maximum deflection and slope at the end of a cantilever beam, which states:

$$y = \left|\frac{Fx^3}{3EI}\right| \tag{1}$$

$$\theta = \left|\frac{Fx^2}{2EI}\right| \tag{2}$$

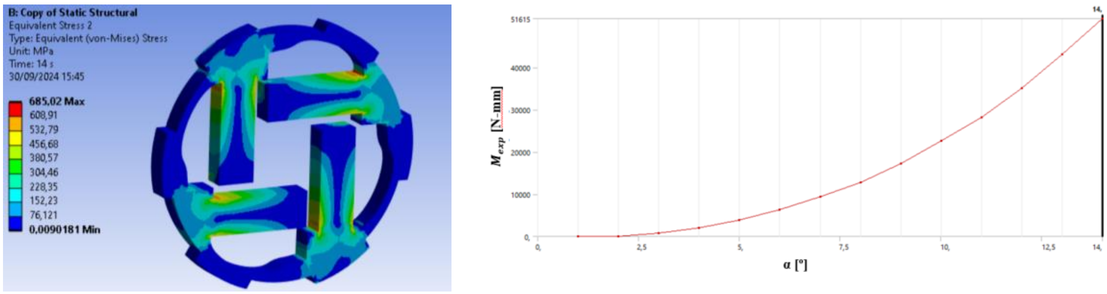
where E represents Young's modulus and I the moment of inertia of the beam. Considering the change of coordinates: $x = a + b\sin(\alpha)$ and $y = b(1 - \cos(\alpha))$, and that the $\vec{F_t}$ is the only force producing torque, it follows:

$$M_{exp} = F_t \cdot s = F \cdot \sin(\alpha - \theta) \cdot s \tag{3}$$

In this model, parameters *a*, *b*, *c*, *d*, and the Young's modulus are design variables influencing material selection. A MATLAB program was developed to optimize these parameters based on the geometric constraints of the exoskeleton's actuation module.

3 RESULTS AND CONCLUSIONS

Based on the obtained optimized parameters, several CAD models were iteratively developed in SolidWorks and analysed through finite element simulations in ANSYS Workbench for rotations of 0 to 14º. This process led to modifications in the optimization program, namely the option to add more springs and the incorporation of maximum stress calculations at the fixed support. Figure 2(a) displays the maximum stress results for the simulation of the actuator rotation, while figure 2(b) shows the moment response. The results confirm the proposed spring's nonlinearity, supporting its potential application in the Elite II actuation module.



(a) *(b)*

Figure 2 – (a) Equivalent von-Mises stress distribution; (b) Moment response.

ACKNOWLEDGEMENTS

The authors acknowledge Portuguese Army, through CINAMIL, and Fundação para a Ciência e a Tecnologia (FCT) for their financial support via the projects ELITE III - Enhancement LITe Exoskeleton, LAETA Base Funding (DOI: 10.54499/UIDB/50022/2020) and LAETA Programmatic Funding (DOI: 10.54499/UIDP/50022/2020).

REFERENCES

[1] G. S. Sawicki, O. N. Beck, I. Kang, and A. J. Young, "The exoskeleton expansion: Improving walking and running economy," *Journal of NeuroEngineering and Rehabilitation*, vol. 17, no. 1, Feb. 2020. doi: 10.1186/s12984-020-00663-9.

[2] N. Van Crey, M. Cavallin, M. Shepherd, and E. J. Rouse, "Design of a Quasi-Passive Ankle-Foot Orthosis with Customizable, Variable Stiffness," in *IEEE International Conference on Rehabilitation Robotics (ICORR)*, Sep. 2023, pp. 1-6. doi: 10.1109/ICORR58425.2023.10304820. PMID: 37941210.

[3] D. F. A. Pires, "Development and analysis of a force element for exoskeleton actuaction", Master's Thesis, Instituto Superior Técnico, Universidade de Lisboa and Academia Militar, Lisboa, Portugal, 2022.

[4] L. F. Quinto, P. Pinheiro, S. Gonçalves, R.Ferreira, I. Roupa, and M. Tavares da Silva, "Development and functional evaluation of a passive ankle exoskeleton to support military locomotion," *Advances in Military Technology*, vol. 17, no.1, pp 79-95, 2022, doi: 10.3849/aimt.01536.