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FINITE ELEMENT ANALYSIS TO COMPARE THE ECOLOGY OF THE LATE JURASSIC THEROPODS *CERATOSAURUS* AND *ALLOSAURUS*. PART I: FEMURS AND LOCOMOTION

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ABSTRACT

Locomotion is a key aspect of animal ecology, and has been studied through a wide variety of methods. Finite Element Analysis (FEA) has been used to study posture in non-avian theropods but has never been used to study differences in their locomotion. This study aims to explore the potential of FEA in this problematic through the application on a *Ceratosaurus* and an *Allosaurus* femur, both from Late Jurassic deposits of Portugal. The femurs show clear differences, with *Ceratosaurus* having a comparatively stronger femur. The significance of this difference is complicated to interpret from an ecological point of view due to the lack of other study exploring this thematic. However, the differences noted here highlight the potential of such methodology on studies related to the locomotion in theropods.

Keywords: Theropoda, Locomotion, FEA, Femur, Late Jurassic.

1. INTRODUCTION

A wide diversity of medium to large size theropods has been identified in the Upper Jurassic of Portugal, with at least five clearly identified genera: *Ceratosaurus*, *Torvosaurus*, *Lourinhanosaurus*, *Allosaurus* and *Lusovenator* (Malafaia *et al.*, 2020 and references therein). Such a diversity of carnivorous

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dinosaurs in the same ecosystem raises questions about their ecology and the possible existence of niche partitioning in these faunae. Locomotion is a very important aspect of animal life and an indicator of their ecology. It has been studied in the fossil record with different tools such as 3D geometric morphometrics (Pintore *et al*., 2022) or by analyzing the trabecular architecture of the femoral head (Gônet *et al*., 2023). Finite Element Analysis (FEA) is a very common tool to study biomechanics and has been used on limbs to investigate locomotion in birds (Wei & Zhang, 2021) or in mekosuchine crocodiles (Stein *et al*., 2020). However, the application of this tool to study locomotion in dinosaurs is still poorly explored. To our knowledge, FEA has only been used on non-avian theropod femurs to investigate the posture of *Daspletosaurus torosus* and *Troodon formosus* (Bishop *et al*., 2018).

In this study we aim to explore the potential of FEA in the investigation and characterization of locomotor habits in non-avian theropods. For that we analyzed the femora of two sympatric theropod of similar size from the Lusitanian Basin: *Ceratosaurus* from Praia de Valmitão (Lourinhã) and *Allosaurus* from the Andrès (Pombal) fossil sites, Portugal (Fig. 1).

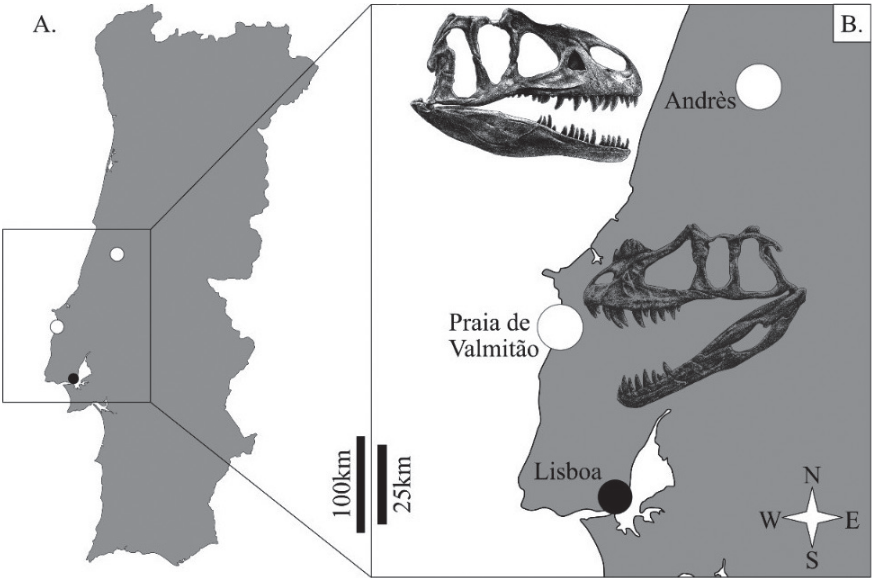

Figura 1. *Ceratosaurus* and *Allosaurus* femora localities. A. Map of Portugal; B. Close up of the localities. *Ceratosaurus* and *Allosaurus* skulls by Marie Aimée Allard (not to scale).

2. OBJECTIVES

By using FEA on solid models (3D), the objective of this study was to determine if *Ceratosaurus* and *Allosaurus* femurs had different structural capabilities that could translate different locomotory habits in those two sympatric theropod dinosaurs.

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3. METHODOLOGY

3.1. Institutional abbreviations

ML, Museu da Lourinhã, Lourinhã, Portugal; MNHN/UL, Museu Nacional de História Natural (Universidade de Lisboa), Lisboa, Portugal; MOR, Museum of the Rockies, Bozeman, USA.

3.2. Material and methods

The right femur of *Allosaurus* MNHN/UL.AND.66 (previously referred to as MNHNUL/AND.001/009; see Malafaia *et al.*, 2007) was analyzed with a computerized tomography scan (CT-scan). The surface was extracted using 3D Slicer. The missing lateral part of the femoral head was sculpted on Blender by copying the lateral part of the left femur collected in the same locality MNHN/UL.AND.67 and interpreted as belonging to the same individual. The left femur was digitized by photogrammetry on Agisoft PhotoScan. The fractures were also filled in on Blender. The right femur of *Ceratosaurus* ML 352 (Antunes & Mateus, 2003) was digitized by photogrammetry on Agisoft PhotoScan. The broken parts of the distal end of ML 352 were also restored on Blender. Models were cleaned and then converted to meshes on Geomagic Wrap. The mesh of ML 352 was then scaled to the volume of the *Allosaurus* femur. Following Bishop *et al*. (2018), isotropic material properties of cortical bones ($E = 17.00\,GPa$, $\upsilon = 0.3$) were applied to the meshes on ANSYS. For both femurs, constraints were applied to both distal condyles and a force of 14710 N (1500 kg), corresponding to the mass estimation of the *Allosaurus* MOR693 (Bates *et al.*, 2012), was applied to the femoral head. An axial and radial component can describe the sagittal force occurring in the femur at any angle and so, following Wei and Zhang (2021), we tested an axial scenario with a ventrally directed load and a radial scenario with a posteriorly directed load (Fig. 2). The use of surface scanning in this study doesn't allow to consider the inner structure of the bones. In 2019, Mielke and Nyakatura showed that consideration of for the inner structure doesn't have any significant impact on femurs and then, we consider that the omission of the inner structures should have minor impact on the results.

4. RESULTS AND DISCUSSION

The results of the FEA show some clear differences between *Ceratosaurus* and *Allosaurus* for both the axial and radial scenarios (Fig. 2). The regions presenting high von Mises stress, corresponding to warm colors, are presenting either tensile or compressive stress. For the axial scenario, both models display the highest stress values below the femoral head and at mid-diaphysis, both of which are visible in lateral view (Fig. 2). For the radial scenario, both models display the highest stress values on the ventral half of both anterior and posterior faces (Fig. 2). However, in both scenarios, *Allosaurus*‘ femur displays the greatest stress patterns. Since *Ceratosaurus*’ femur is stronger in both the axial and radial scenarios, we can infer that it is stronger in all sagittal force occurring in the bone at any angle. For theropods of similar size such as *Ceratosaurus* and *Allosaurus*, it is reasonable to assume that the differences noted between the two femurs can be correlated to diverse locomotion mechanics. However, the lack of studies on this issue doesn't allow us to draw conclusions about the significance of the differences noted in this analysis. Future studies with a larger sample and more well-known taxa could allow a better understanding of the ecological significance of these differences.

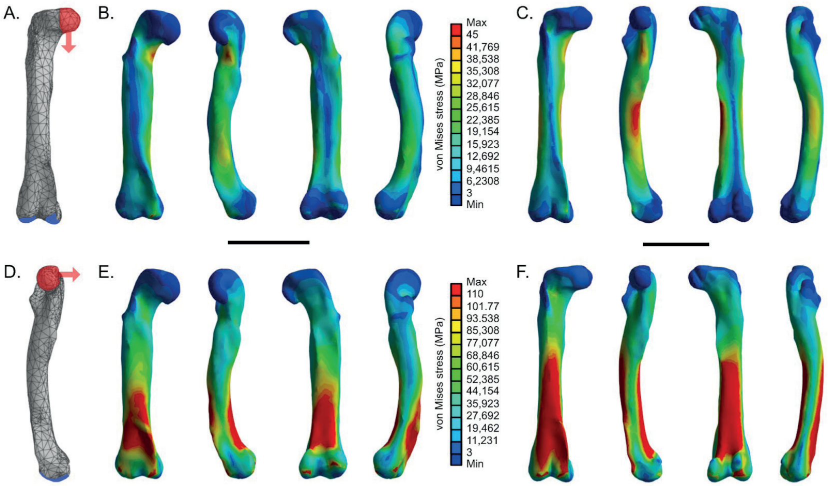

Figura 2. Free body diagram for the axial (A) and the radial scenario (D) with forces in red and constraints in blue on *Allosaurus* femur mesh. Von Mises stress for the axial analysis on *Ceratosaurus* (B) and *Allosaurus* (C) and the radial analysis on *Ceratosaurus* (E) and *Allosaurus* (F) in, from left to right, anterior, medial, posterior, and lateral views. Scale bar: 25cm.

5. CONCLUSION

The use of FEA on the femurs of theropods has rarely been performed. The comparison of the mechanical capabilities of the femurs of *Ceratosaurus* and *Allosaurus* reveals that the first was stronger than the latter for any angle of the bone. The application of FEA to investigate locomotion in both extinct and extant taxa is still poorly explored, which makes the interpretation of these differences complicated. The diverse patterns of stress distribution noted should translate some kind of locomotion differences in those two sympatric theropods. However, more studies are needed to understand this signal from an ecological point of view.

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