How to simulate soft tissues in extinct animals. Using sauropod dinosaurs as a case study

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EXTENDED ABSTRACT

1 Introduction

Sauropod dinosaurs, with their greatly elongated neck and tails [1] have always caught the attention of the public. These animals lived between ca. 220 and 66 million years ago, and reached enormous sizes, with estimated masses comparable with that of commercial jet planes [2]. Such large sizes were accomplished thanks to the peculiar features of their skeletal apparatus, having a series of air sacks as part of the respiratory apparatus, which enfold and penetrate most of the neck and back vertebrae [3]. These air sacks were located within the vertebral centra, limiting the development of the bone, and creating vertebrae with an H-shaped cross-section, thus lightening the skeleton without compromising the ability to sustain loads [4]. The shape of the skeleton of these animals has always caught the attention of researchers since their first findings, leading to various hypotheses during the course of the years, from being too large to walk on land (thus being aquatic animals) to using their tails as a defensive weapon [5]. From the observation of the fossils and the finding of more elements and more species, some hypotheses have been corroborated, while others have been refuted. Due to the size of the elements, their rarity and their fragility, manual handling is difficult, so computer simulations, and in particular, the Multibody Dynamics simulation can be of great help in understanding these animals [6]. In the past several computer simulations were performed, mainly to address the range of motion of the bones, to estimate the amplitude of movement that the elements were capable of [7], [8], the walking capability [9], and tail dynamics [10]–[12]. Yet the main issue for computer simulation is the simulation of the action of soft tissues on the articulations since we have no direct evidence of the distribution of the tissues nor living animals with similar characteristics. Several attempts were made to recreate the organization of the musculature in sections of the body of these animals, with particular emphasis on the tail [13] and the neck [4], [13]–[17].

2 Methods

The models of tails and necks were built within multibody dynamic simulation software. A model of the tail was built and run using ADAMS software, whereas the rest of the models, of the tail and neck, were built and run using MBDyn software (http:// mbdyn. org/). The models are built starting from data collected from the literature. The simulation performed using ADAMS does not feature any unilateral constraint to limit the extension of the relative motion between parts, while all the simulations performed using MBDyn feature the constitutive law implemented in the “cont-contact” module. This module limits the movement using a continuous contact formulation that applies a reaction force upon reaching the maximum angle imposed on the model. It is derived from the model originally proposed by Hunt and Crossley [18] and subsequently enhanced by Flores et al. [19] to provide the desired restitution rate based on the actual velocity at the contact. The simulation of the tail is further improved by adding the drag resulting from interaction with the air, with the approximative formula:

$$drag_{air} = \frac{1}{2}\rho {v_{\perp}}^2 S C_D.$$

considering the density of air (ρ) at sea level at 15 °C, equal to 1.225 kg/m3; the component of velocity ($v_{\perp}$) perpendicular to the element; the section (S) of the element given by the length of the segment multiplied by its average diameter, assuming cylindrical segments with the corresponding drag coefficient (C_D) of 0.5.

3 Discussion and Conclusions

The simulation performed using ADAMS without any parameter to simulate the action of the soft tissue was able to achieve greater velocities than the model simulated in MBDyn with the parameters to simulate the damping action of the soft tissues and the action of air drag acting on the model. The difference is imputable to the action of the parameters simulating the soft tissues rather than a difference between the software used. However, the calibration of such parameters is difficult, and must be performed by hand observing the results since no data is available in the literature. The simulation of the neck featured two models of organization of the nuchal ligament which connects the vertebrae: one model follows the hypothesis of each vertebra connected to the two adjacent elements [20] and the other model follows the hypothesis of each vertebra connected with elements distant two positions, so that a ligament connects two vertebrae separated by two other vertebrae, creating a net of overlapping ligaments [17]. The two simulations aimed at maintaining the model of the neck in a sub-horizontal position, with only the gravity acting on the model, and regulating the intensity of the force generated by the rod elements, positioned in a manner to simulate the ligaments in the two hypotheses.

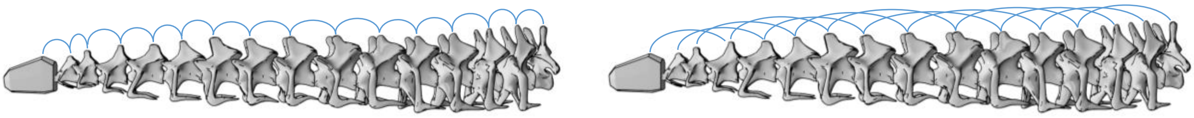

Figure 1: Organization of the nuchal ligament with respect to the two hypotheses

The results of the simulation highlighted that the rod elements connected to the adjacent elements develop forces roughly equal to a third of the force generated by the corresponding element in the other simulation, seemingly indicating it as the most advantageous model. The use of multibody dynamic simulations for extinct animals is a powerful instrument, capable of answering questions not addressable in the past. Yet it remains an instrument, whose results must be interpreted, and the simulation of the action of the soft tissues is of great importance, even when such information is lacking. The main difficulties observed during these simulations is the parameterization of the limit of the range of motion, and the damping effect of the soft tissues. Further studies are needed to better address the proportion in which elements participate in these phenomena.

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