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Simplified three-dimensional model provides anatomical insights in lizards' caudal autotomy as printed illustration

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ABSTRACT

Lizards' caudal autotomy is a complex and vastly employed antipredator mechanism, with thorough anatomic adaptations involved. Due to its diminished size and intricate structures, vertebral anatomy is hard to be clearly conveyed to students and researchers of other areas. Three-dimensional models are prodigious tools in unveiling anatomical nuances. Some of the techniques used to create them can produce irregular and complicated forms, which despite being very accurate, lack didactical uniformity and simplicity. Since both are considered fundamental characteristics for comprehension, a simplified model could be the key to improve learning. The model here presented depicts the caudal osteology of *Tropidurus itambere*, and was designed to be concise, in order to be easily assimilated, yet complete, not to compromise the informative aspect. The creation process requires only basic skills in manipulating polygons in 3D modeling softwares, in addition to the appropriate knowledge of the structure to be modeled. As reference for the modeling, we used microscopic observation and a photograph database of the caudal structures. This way, no advanced laboratory equipment was needed and all biological materials were preserved for future research. Therefore, we propose a wider usage of simplified 3D models both in the classroom and as illustrations for scientific publications.

Key words: anatomy, 3D modeling, teaching, learning, *Tropidurus itambere*.

INTRODUCTION

Modern science is highlighting the importance of integrative and interdisciplinary approaches to undergraduate biology teaching (as pointed out by several reports such as the Bio2010), in the aim to strengthen the neural pathways that consolidate true and deep learning. Identifying difficulties in the learning process or in the information conveyance is of great importance to improve the effectiveness of communication within the scientific community. We personally observed that students, and even teachers from other fields, usually found it hard to comprehend the anatomical features involved in autotomy, but that images of a simplified three-dimensional model greatly facilitated their understanding.

The term autotomy (from the Greek autos = "self" and tomos = "cutting") refers to the voluntary act of self-amputation, that occurs in a controlled manner, along well established fracture planes, and usually as a last resort in response to a predator attack (Cooper Jr 2003, Maginnis 2006, Bateman and Fleming 2009). Lizards are

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noteworthy for their particularly complex ability to shed and regenerate their tails (Alibardi 2010). The saxicolous lizard *Tropidurus itambere* Rodrigues, 1987 inhabits rocky outcrops throughout South America (Rodrigues 1988), resorting to autotomy as an anti-predator tactic (Van Sluys et al. 2002).

Volume visualization is the method of comprehension of a volumetric object or situation through interactive graphics or imaging techniques (Kaufmann 2000). Since anatomical structures usually present complex spatial organization in three dimensions, visual representation with the conversion of the structure in a simpler pattern of geometric forms can facilitate the creation of a mental model that can be easily recalled, promoting and enhancing the learning process (Miller 2000, Garg et al. 2001).

This paper will address two main issues concerning 3D modeling in the context of propagating knowledge: 1) the benefits of developing a simplified tridimensional model, regarding the creation process aspects and the easiness of assimilation; and 2) the possibility of presenting volumetric solids as printed images without significant prejudice to the informative contents, and the advantages of using those images as scientific illustrations.

The Process of Autotomy and its Anatomical Peculiarities

To ensure the success and easiness of autotomy, the tissues involved in this process present several adaptations, such as musculature arranged in segmented display, with cartilaginous septum preventing tissue damage when tail is severed, and muscular sphincters along the main caudal artery, which constrict its flow, avoiding unnecessary blood loss during autotomy (Arnold 1984, Bellairs and Bryant 1985, Payne 2012).

One of the most remarkable features involved in the occurrence of autotomy is the intervertebral breakage, which literally splits the vertebrae in two, resulting in the derived, yet most common form of autotomy (Woodland 1920, Arnold 1984). The presence or absence of the intravertebral fracture plane in a vertebra is associated not only with the capacity to release that portion of the tail, but also with its subsequent regeneration (Etheridge 1967). That is because from the exposed bone surface of the broken vertebra, a cartilaginous hollow tube will originate, which will serve as the backbone for the regenerated tail, providing mechanical support and fixation points to the growing tissues (Barber 1944, Hughes and New 1959, Alibardi 2010).

The fracture plane location within the vertebrae is associated with a number of anatomical structures, such as the transverse processes, the neural arch and the hemal process (Arnold 1984), in a complex arrangement. Therefore, lizards' caudal and vertebral osteology have been fairly explored since autotomy has drawn the attention of researchers (*e.g.* Woodland 1920, Etheridge 1967, Ritzman et al. 2012, Sanggaard et al. 2012), in an attempt to enlighten the mechanisms underlying tail severing and regeneration.

For undergraduate students and even for scholars from other fields, one of the most critical impairments to fully understanding the subtleties of this process concerns the structural features of lizards' vertebrae. Because of its particularly complex set of structures, vertebrae's anatomy is not very easily assimilated through regular means of scientific illustration and written description (J.D. Amorim, personal observation), due to the fact that these means of communication do not facilitate the development of a mental model of volumetric forms. It has been shown that self-directed examination of an object, from multiple perspectives and different views can greatly improve spatial learning (Garg et al. 2001).

However, the diminished size of the vertebral structures can make proper handling tricky and impair detailed observation, compromising the understanding. We were able to notice that undergraduate students frequently found it difficult to form a mental model, and thus were usually unable to accurately place and correlate the structures described in the textbooks, finding it arduous to comprehend the peculiarities of the autotomy.

Virtual Models as Consolidated Teaching Tools

Three-dimensional modeling is proving to be a powerful tool in unveiling anatomical particularities, especially within the context of functional anatomy, where morphological features interact in complex physiological mechanisms (El-Khalili 2005, Lu et al. 2010, Lee et al. 2010, Ruisoto et al. 2012). It has also solved a multitude of practical issues and inconveniences of working with the actual structures to be studied, which could result in being expensive and time consuming, not to mention ethically questionable (McLachlan and De Bere 2004, Peat and Taylor 2005, Oakley 2012).

A number of different techniques are available to digitalize a solid form, such as 3D-MRIs or CT-scans, maximum intensity projection (MIP), high-resolution digital photographs of cross-sections, weighted distance transform (WDT), stereoscopic view, *inter alios* (Johnson et al. 1998, Anastasi et al. 2007, Kerwin et al. 2010, Lu et al. 2010, Adams and Wilson 2011, Moreno et al. 2012, Ribaupierre and Wilson 2012), most of which rely upon digital imaging devices or resort to previously gathered medical records and images, vastly available in a number of databases for human beings, but not quite as much for animals.

Techniques such as the ones mentioned above, although very accurate and reliable in their representation of the concerned object, lack the didactic component of the schematic drawings. In that regard, Miller (2000) pointed out that gross anatomy fundamentals are better learned from simpler patterns that highlight the principles of collinearity and symmetry, rather than from analyzing the real anatomical parts, which could lead to confusion in a first contact.

In scientific publications, where it is of utmost importance to convey the intended message as clearly as possible for the greatest plausible range of audience, it is important to find ways to simplify complex systems and yet detail intricate structures. That is why researchers usually rely on scientific drawings to expose their findings, and that is why simplified 3D models could better serve this purpose.

Potential Application of 3D Models as Scientific Illustrations

To the best of our knowledge, volumetric visualization has yet to be further explored in zoological and biological publications, especially regarding lizards caudal anatomy. Kuhn et al. (2008) presented some Micro-CT obtained 3D images of the caudal vertebras of two Australian lizards, evidencing the fracture plane and related structures. Despite their great breakthrough in offering an innovative method for illustrating anatomical features involved in autotomy, the images presented could appear confusing to the unfamiliarized observer, as image artefacts can confer a distorted aspect to structures and surfaces.

Most of the studies involving three-dimensional models try to validate them as a substitute for practical lessons, comparing the performance of students learning from a virtual reality simulation with that from students subjected to regular dissection/experimental practices (e.g. Quinn et al. 2009). Such comparisons not always allow for unanimous conclusions, leaving questions as to the final results of such methods. Our goal with this communication is to direct the use of 3D models (and perhaps expand it), not just as a computer based teaching tool, but as a means to illustrate academic papers, or to complement publication images.

Even though regular scientific illustrations provide some helpful insights regarding the indicated structures, they may require a level of familiarity with the object depicted to ensure true comprehension, while 3D models can be more easily assimilated at first contact (Hoyek et al. 2011). However, the majority of scientific propagation is still 2D or print based (El-Khalili 2005), so combining the best of two worlds (turning 3D models into printed images) could be the key to facilitate learning and understanding, given the most common means of knowledge dissemination.

Moreover, it seems that printed versions of three-dimensional objects (photographs or rendered images) are as good as the interactive computer-based models in enhancing the spatial abilities required in the process of anatomical learning. Appelhof et al. (2008) tested students learning from a 3D model exhibited in a computer device with the ones exposed to 2D printed versions of the same model, and Hoyek et al. (2011) compared the performance of students learning from an interactive PDF 3D femur model with others who have learned from photographs of the same bone structure. Both studies found no differences in the acquired skills of the subject from experimental groups, although showing improvement in those experimental groups when compared to the control groups (learning without aid of any 3D imagery), showing that, although volumetric visualization is of great use to the learning process, it is not necessary to present the models in a computer-based system.

That being true, volumetric visualization could step out of computer platforms to be spread throughout regular dissemination tools such as textbooks and article papers, as a promising substitute for scientific illustration when detailed and complex forms are to be presented, or for introducing new structures to an unfamiliarized audience.

Creating our Simplified Virtual Model

The model presented here is a volumetric representation of the vertebral skeleton of *Tropidurus itambere*, a small to medium sized lizard, relatively common around the area of study (Van Sluys 2000, Nunes et al. 2007). Regarding autotomy's mechanisms, the anatomical features of *T. itambere* can typify those of congener species, and even be associated with those of other iguanids with similar vertebral osteology (Etheridge 1967).

To serve as reference for the 3D modeling we used dissected full tails and autotomized caudal portions of *T. itambere*, all from the herpetological collection of the Federal University of Juiz de Fora (UFJF). Because the structures were so small and fragile, we analyzed them through microscopic observation, and compiled a database of high definition macro photographs from a multitude of different angles to use as guidance in the modeling process (Figure 1). The process did not destroy or

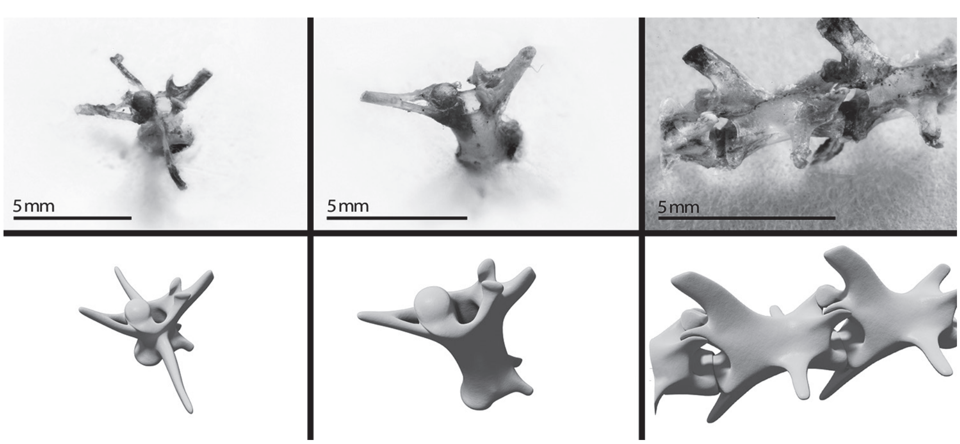

Figure 1 - *Tropidurus itambere* vertebrae photographs and the respective volumetric models they originated.

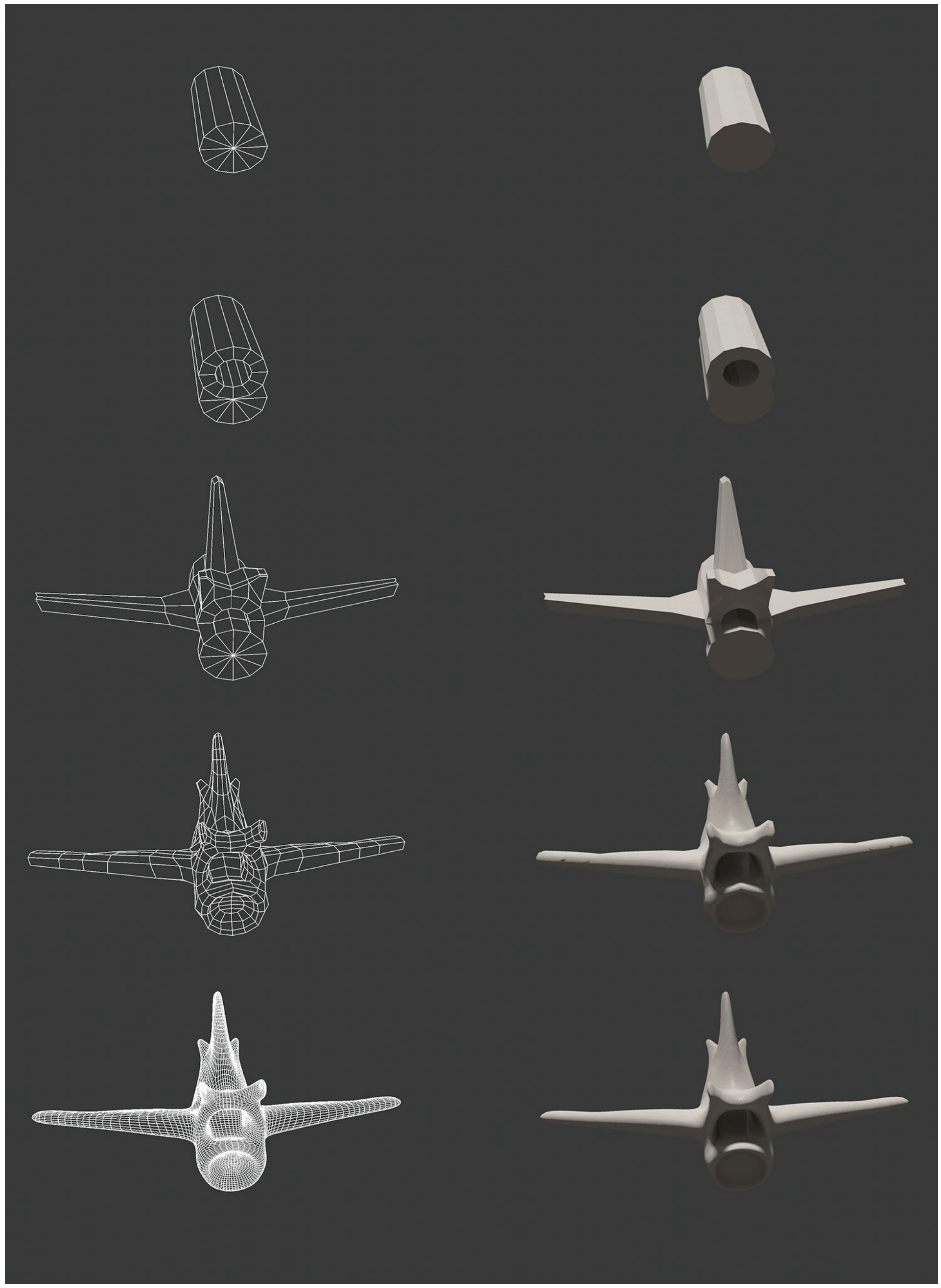

Figure 2 - Sequence of progress in the modeling process. The column on the left presents the polygonal grid visualization and the column on the right presents the solid view.

permanently damage the biological material, nor did it require any specialized laboratory equipment or rigorous procedures, as many of the methods which are usually employed to create digital models, do.

This model was created using the software Autodesk Maya 2012 for the initial structural modeling, through manipulation of basic geometrical solids, which were later exported to Pixologic Zbrush 4 for additional detailing and softening of the forms (Figure 2). Once the model was completed, it could be rotated and positioned as we desired, and rendered images could be obtained from any possible angle.

3D modelling is an artistic task, and therefore requires some degree of artistic skills combined with a minimum level of familiarity with one of a range of commercially available rendering softwares. Scientific drawing also requires specific tools and skill, and takes about the same amount of time and effort. Furthermore, digital modeling can also be outsourced, as often occurs with scientific drawing, seeing that this is now an expanding field. Therefore, using 3D models as illustration for papers is just a matter of changing the approach, and can be very advantageous for depicting detailed or complex structures.

CONCLUSIONS

Our digital model was initially meant to be rendered for printed illustration in a master's degree thesis on ecological and morphological features involved in the intravertebral autotomy and posterior tail regeneration (Figure 3). The aim was to create a model simple enough to be easily understood without jeopardizing informative quality, to serve as illustration and to be presented to undergraduate students in classes focused on caudal anatomy and autotomy.

However, we did not anticipate the astonishing success of the images in facilitating the learning process of virtually every student who was exposed to the images. That drew our attention to a window of possibilities that simplified virtual models present both in science education and in scientific publications, which are currently being overlooked within most of the biological areas.

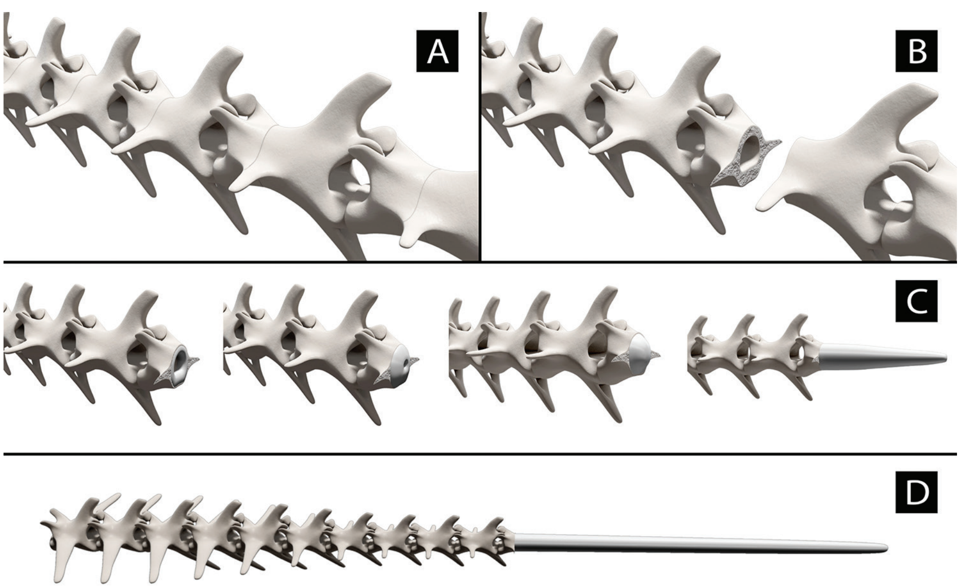

Figure 3 - Original illustration rendering, showing the autotomy's osteological peculiarities of *Tropidurus itambere*. **A:** Intravertebral fracture planes; **B:** The occurrence of autotomy in a vertebrae; **C:** Four stages of cartilage regeneration; and **D:** Fully regenerated tail with cartilaginous stick replacing the vertebrae.

With the methodology proposed here, the process of creating a 3D model can be just as easy as the process of creating any other scientific illustration, and the results obtained by volumetric visualization, even when printed, are much more positive in terms of general comprehension of the forms presented than those of regular drawings. Therefore we strongly encourage a more prominent use of simplified three-dimensional models in articles, text books and any other mean of scientific dissemination.

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RESUMO

A autotomia caudal é um mecanismo anti-predação complexo e amplamente utilizado por lagartos, que envolve diversas adaptações anatômicas. Por seu tamanho diminuto e estruturas intrincadas, é difícil explicar claramente a anatomia vertebral para estudantes e pesquisadores de outras áreas. Modelos tridimensionais são ferramentas prodigiosas no esclarecimento de nuances anatômicas. Algumas das técnicas usadas para criá-los produzem formas complicadas e irregulares, que ainda que primem pela exatidão, não apresentam uniformidade e simplicidade. Como ambas são consideradas características fundamentais para a compreensão, um modelo simplificado poderia ser a chave para melhorar a aprendizagem. O modelo aqui apresentado ilustra a osteologia caudal de *Tropidurus itambere*, e foi desenvolvido para ser conciso, de maneira a ser facilmente compreendido, mas completo, não comprometendo o caráter informativo. O processo de criação requer apenas habilidades básicas de manipulação de polígonos em softwares de modelagem 3D, além do conhecimento apropriado da estrutura a ser modelada. Como referência para a modelagem usamos observações microscópica e uma base de fotografias das estruturas caudais. Assim, não se fez necessário ou uso de nenhum equipamento laboratorial avançado, e todos os materiais biológicos foram preservados para futuras pesquisas. Portanto, propõe-se maior utilização de modelos 3D simplificados tanto em sala de aula quanto como ilustrações em publicações científicas.

Palavras-chave: anatomia, modelagem 3D, ensino, aprendizado, *Tropidurus itambere*.

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