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Finite element analysis of the cranium: Validity, sensitivity and future directions

Analyse par éléments finis du crâne : validité, sensibilité et directions futures

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ABSTRACT

Finite element analysis (FEA) is increasingly applied in skeletal biomechanical research in general, and in fossil studies in particular. Underlying such studies is the principle that FEA provides results that approximate reality. This paper provides further understanding of the reliability of FEA by presenting a validation study in which the deformations experienced by a real cadaveric human cranium are compared to those of an FE model of that cranium under equivalent simulated loading. Furthermore, model sensitivity to simplifications in segmentation and material properties is also assessed. Our results show that absolute deformations are not accurately predicted, but the distribution of the regions of relatively high and low strains, and so the modes of global deformation, are reasonably approximated.

RÉSUMÉ

La méthode des éléments finis (FEA) est de plus en plus appliquée en recherche biomécanique du squelette en général, et dans les études de fossiles en particulier. Ces études sont fondées sur le principe selon lequel les FEA fournissent des résultats qui se rapprochent de la réalité. Cet article fournit une meilleure compréhension de la fiabilité de la méthode des FEA, en présentant une étude de validité dans laquelle les déformations subies par un vrai crâne de cadavre humain sont comparées à celles d'un modèle par éléments finis de ce crâne sous une charge simulée équivalente. En outre, la sensibilité du modèle vis-à-vis de simplifications dans la segmentation et des propriétés des matériaux est également évaluée. Nos résultats montrent que les déformations absolues ne sont pas prédites avec précision, mais que la répartition des régions de relativement hautes et basses contraintes, et par conséquent les modes de déformation globale, sont raisonnablement estimés.

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1. Introduction

Over the last twenty years, finite element analysis (FEA) has increasingly been applied in functional morphology and the biomechanics of extinct and living vertebrates (Rayfield, 2007; Richmond, 2007; Ross, 2005). It has been used to predict the mechanical behaviour of fossil material and so to infer function and ecology. However, the legitimacy of FEA is grounded on the premise that finite element models (FEM) reflect the mechanical behaviour of the real structures they represent, that they produce valid results. The present paper extends previous work that assessed the validity of a model of the human cranium when simulating incisor bites (Toro-Ibacache et al., 2016). In this prior study, FEA approximated but did not exactly replicate experimentally measured strains. In particular, while the mode of deformation was reasonably approximated, the magnitudes were not. Further sensitivity analyses showed that the mode of deformation was altered little by varying the segmentation approach (i.e. what parts of the model segmentation are assigned to and given the material properties of teeth, cortical or cancellous bone), but the magnitudes of deformation were reduced approximately proportionately as the model was made more dense by replacing cancellous with cortical bone. Thus, in this model when simulating an incisor bite, a simple segmentation that preserves geometry (i.e., external form and major internal cavities) but effectively treats the whole of the rest of the cranium as if it were solid, and made of cortical bone and teeth approximated the mode of deformation found in experimentation with the real cranium. In this paper, we extend this work to a simulated molar bite, to assess validity and sensitivity using the same cranium.

To assess validity, results from a finite element analysis (i.e., stress, strain and deformation) should match those obtained from the real specimen when the same loading regimen is applied (Bright and Rayfield, 2011; Grine et al., 2010; Kupczik, 2008; Rayfield, 2007; Richmond et al., 2005). While some studies have measured strains experienced by skeletal elements *in vivo* (Ross, 2001; Rubin and Lanyon, 1982) carrying out physical loading experiments on living individuals carries with it both ethical and practical difficulties which limit its use, as such, usually measurements are taken from loading experiments *ex vivo* with postmortem material (Bright and Rayfield, 2011; Groning et al., 2009; Kupczik et al., 2007; Richmond et al., 2005; Strait et al., 2005; Szwedowski et al., 2011). As such, validation studies have typically compared the strain magnitudes and/or vector orientations experienced by a specimen *ex vivo* with those predicted by the virtual finite element model following the simulation of a load (Bright and Rayfield, 2011; Szwedowski et al., 2011).

Until recently the most viable option to measure deformations was to affix strain gauges to bone (Bright and Rayfield, 2011; Daegling and Hylander, 2000; Ichim et al., 2007; Kupczik et al., 2007; Richmond et al., 2005; Strait et al., 2005; Szwedowski et al., 2011; Vollmer et al., 2000). However, these present some limitations (Richmond et al., 2005), which include technical difficulties associated with fixing gauges (Groning et al., 2009) and limits to the number of gauges that can be applied leading to the impossibility of dense measurement of strains being collected over regions of interest (Bright and Rayfield, 2011; Evans et al., 2012; Groning et al., 2009, 2012; Yang et al., 2007). To overcome these limitations, digital speckle pattern interferometry (DSPI) has been applied to measurement of bone surface strains in validation studies (Bright and Groning, 2011; Groning et al., 2009, 2012; Toro-Ibacache et al., 2016). This is an optical full-field strain measurement technique that allows strains to be directly measured over a small area (several cm^2), determined by the field of view of the device.

Most validation studies have reported a degree of success in predicting skeletal behaviour using FEA. This said, models often fail to accurately reproduce absolute strain magnitudes while relative strain magnitudes between different regions of the model are generally consistent with relative strains from experimental loadings of the real specimen (Bright and Rayfield, 2011; Kupczik et al., 2007; Strait et al., 2005; Toro-Ibacache et al., 2016). With regard to the cranium, it has been suggested that differences between the performance of *in silico* models and actual skeletal material may be related to regional differences in material properties, to the presence of complex patterns of heterogeneity and orthotropy, and the difficulty in correctly reproducing variations in cortical bone thickness and cancellous bone architecture, given the constraints of imaging and model building (Bright and Rayfield, 2011; Ross, 2005; Strait et al., 2005; Szwedowski et al., 2011). This suggestion arises from studies that report regional differences in material properties of cortical bone in the human craniofacial skeleton (Dechow et al., 2010; Peterson and Dechow, 2002, 2003; Peterson et al., 2006). On the other hand, strain orientation in validations is commonly consistent between virtual and physical specimens (Bright and Rayfield, 2011; Cuff et al., 2015; Porro et al., 2013; Toro-Ibacache et al., 2016). With regard to issues with resolution, and so segmentation, of cortical and trabecular bone, sensitivity analyses suggest that these mainly affect strain magnitudes (overall model stiffness), but less so strain vector orientations and relative strains (Fitton et al., 2015; O'Higgins and Milne, 2013; Parr et al., 2012; Toro-Ibacache et al., 2016).

While it would be desirable to have virtual models that exactly reproduce the performance of the real specimens, this can only be known for certain if experimental data for the full surface are available to guide model building. In most cases this is not possible, yet FE models are still useful to predict relative strains within and among models which renders FEA a useful approach with respect to many questions (Bright and Rayfield, 2011; Milne and O'Higgins, 2012; O'Higgins and Milne, 2013; Strait et al., 2005), including the comparative cranial and post-cranial biomechanics of hominoids (Richmond, 2007; Wroe et al., 2007, 2010), hominins (Strait et al., 2009, 2010; Wroe et al., 2010) and recent human populations (Püschel, 2013).

Unknown input parameters and model simplifications are inevitable, particularly for studies of fossil hominins. As such, in order to improve accuracy of FE strain prediction and better understand the modelling process, sensitivity analyses should be carried out to assess how differences in model building approaches impact predicted strains and forces. Previous studies have examined the effects of