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Research article

Occlusal load distribution through the cortical and trabecular bone of the human mid-facial skeleton in natural dentition: A three-dimensional finite element study

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ABSTRACT

Understanding of the occlusal load distribution through the mid-facial skeleton in natural dentition is essential because alterations in magnitude and/or direction of occlusal forces may cause remarkable changes in cortical and trabecular bone structure. Previous analyses by strain gauge technique, photoelastic and, more recently, finite element (FE) methods provided no direct evidence for occlusal load distribution through the cortical and trabecular bone compartments individually. Therefore, we developed an improved three-dimensional FE model of the human skull in order to clarify the distribution of occlusal forces through the cortical and trabecular bone during habitual masticatory activities. Particular focus was placed on the load transfer through the anterior and posterior maxilla. The results were presented in von Mises stress (VMS) and the maximum principal stress, and compared to the reported FE and strain gauge data. Our qualitative stress analysis indicates that occlusal forces distribute through the mid-facial skeleton along five vertical and two horizontal buttresses. We demonstrated that cortical bone has a priority in the transfer of occlusal load in the anterior maxilla, whereas both cortical and trabecular bone in the posterior maxilla are equally involved in performing this task. Observed site dependence of the occlusal load distribution may help clinicians in creating strategies for implantology and orthodontic treatments. Additionally, the magnitude of VMS in our model was significantly lower in comparison to previous FE models composed only of cortical bone. This finding suggests that both cortical and trabecular bone should be modeled whenever stress will be quantitatively analyzed.

1. Introduction

Distribution of occlusal forces through the mid-facial skeleton in natural dentition had traditionally been explained to occur along specific osseous trajectories known as buttresses (Cryer, 1916; Sicher and Tandler, 1928; Rowe and Williams, 1985). The buttresses were anatomically described as areas in the mid-facial bones that have a form of vertical and horizontal pillars (Fig. 1) composed of a thick cortical bone (Cryer, 1916). Seven vertical buttresses were proposed to transfer most of the occlusal load (Fig. 1A), while three horizontal buttresses (Fig. 1B) were suggested to stabilize the vertical buttresses mechanically by interconnecting them at different levels (Cryer, 1916; Sicher and Tandler, 1928; Rowe and Williams, 1985).

Occlusal force distribution was studied further in dry skulls using strain sensitive transducers, also known as strain gauges (Endo, 1965, 1966, 1970). When attached to the facial bone surface, this device registered bone microdeformations in response to artificial tooth loading. During such experiments, Endo (1965, 1966, 1970) detected mainly compressive deformations in the cortical bone along the vertical buttresses and simultaneous tensile deformations in the region of the horizontal buttresses. Endo (1965) also found the highest strain magnitude in the maxillary cortex above

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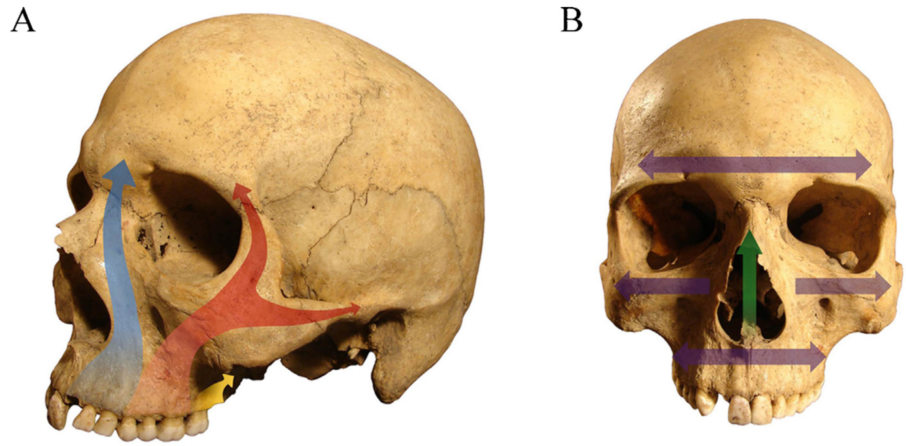

Fig. 1. Buttresses of the mid-facial skeleton. (A) The nasomaxillary buttress (blue arrow), the zygomaticomaxillary buttress (red arrow), and the pterygomaxillary buttress (yellow arrow); (B) The sagittal buttress (green arrow), the frontal buttress (upper violet arrow), the zygomatic buttress (middle violet arrows), and the maxillary buttress (lower violet arrow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the anterior teeth, which decreased gradually as the strain gauge was moved distally along the dental arch. Similar to Endo's findings, Alexandridis et al. (1981, 1985) reported that occlusal forces in the photoelastic skull models distribute predominantly over the anterior maxilla. The skull models used in these studies were formed of a birefringent material, loading of which causes the incident beam of polarized light to split in the direction of stress distribution (Alexandridis et al., 1981, 1985). Although these studies revealed important data related to the mechanical behavior of cortical bone during occlusal loading, neither the contribution of all masticatory muscles nor the role of trabecular bone in the occlusal force distribution were possible to assess by these techniques.

Recent application of finite element (FE) method appeared the most promising for clarifying the pattern of occlusal load distribution through the mid-facial bones (Tanne et al., 1988). However, few published FE studies addressing this problem provided conflicting results that, in some cases, differed significantly from the theory of buttresses and/or strain gauge data. During the simulation of biting, Cattaneo et al. (2003) reported that distribution of von Mises stress (VMS) follows the route of the vertical buttresses, whereas Gross et al. (2001) observed that VMS splits above the loaded tooth and dissipates in two directions different from buttresses. More recently, Prado et al. (2012, 2013) measured VMS along the vertical buttresses during biting, and concluded that stress distributes unevenly through the mid-facial skeleton. Gross et al. (2001) also simulated clenching and described almost uniform distribution of occlusal stress. These studies frequently used oversimplified skull models created only of cortical bone. Bone elastic properties and the magnitude of force applied to the teeth, accurate selection of which is crucial for FE analysis (Strait et al., 2005; Gröning et al., 2012), differed significantly from the experimentally calculated values in healthy dentate individuals. Moreover, these studies did not provide direct evidence for occlusal stress distribution, particularly through the cortical and trabecular bone compartments individually.

In general, there is a need for more detailed investigation of occlusal load distribution through the mid-facial bones in the natural dentition because alterations in magnitude and/or direction of occlusal forces may cause remarkable changes in both cortical and trabecular bone structure (Bresin et al., 1994, 1999; Mavropoulos et al., 2004, 2005; Tanaka et al., 2007; Canullo and Götz, 2012; Hasan et al., 2014). Such changes were detected not only in the alveolar bone, but also at the distant sites, e.g. in the zygomatic (Kato et al., 2004; Yoshino et al., 2007) and frontal bones (Dechow et al., 2010).

Therefore, the aim of our study was to clarify the distribution of occlusal forces through the cortical and trabecular bone of the mid-facial skeleton during habitual masticatory activities. Particular focus was on the patterns of load transfer in the anterior and posterior maxilla. In order to overcome simplifications used in previous FE studies, we developed an improved 3D skull model with both cortical and trabecular bone compartments, hollow structures within the mid-facial bones, and jaw-closing muscles. The results presented in equivalent von Misses stress (VMS) and maximum principal stress values were analyzed both qualitatively and quantitatively, and compared with previous finite element studies and patterns of bone strain registered in dry human skulls.

2. Material and methods

2.1. Modeling of the skull

A computer model of the skull was created using CT images of a dry skull of a young adult Caucasian male with the fully dentate maxilla (Fig. 2A). Sexually dimorphic features were moderately expressed so that the skull presented an average anatomical situation. The skull was chosen from the skeletal collection of the Laboratory for Anthropology (Institute of Anatomy, Faculty of Medicine, University of Belgrade), and scanned by Computed Tomography (Siemens Somatom Sensation 16) in 0.75 mm thick axial sections parallel to the Frankfurt plane (Fig. 2B). The CT images were then imported into Mimics visualization software (version 10.1, Materialize, Leuven, Belgium) in which cortical bone, trabecular bone, and teeth were modeled separately and joined in the full skull model. On each CT slice, bone areas were automatically segmented by thresholding and extracted in the temporary skull mask. Hollow structures within the facial skeleton, e.g. the paranasal sinuses, were also created during this step. By combining thresholding and the Boolean operations, individual masks representing cortical and trabecular bone were subtracted from the temporary skull mask, respectively (Fig. 2C). Trabecular bone was modeled as a solid structure, because resolution of CT images was not sufficient for the precise 3D reconstruction of trabecular network. The segmentation was also used for teeth modeling. A mesh of linear tetrahedrons generated by TetGen (Hang Si, WIAS, Berlin, Germany) is shown in Fig. 2D. An average element size of 0.25 mm, 1.0 mm, and 2.5 mm was used for cortical bone, trabecular bone, and teeth, respectively. The total number of finite elements and nodes representing each tissue is listed in Table 1.