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Finite element analysis of equine incisor teeth. Part 2: Investigation of stresses and strain energy densities in the periodontal ligament and surrounding bone during tooth movement

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ABSTRACT

This study investigated the hypothetical contribution of biomechanical loading to the onset of equine odontoclastic tooth resorption and hypercementosis (EOTRH) and to elucidate the physiological age-related positional changes of the equine incisors. Based on high resolution micro-computed tomography (μCT) datasets, 3-dimensional models of entire incisor arcades and the canine teeth were constructed representing a young and an old incisor dentition. Special attention was paid to constructing an anatomically correct model of the periodontal ligament (PDL). Using previously determined Young's moduli for the equine incisor PDL, finite element (FE) analysis was performed. Resulting strains, stresses and strain energy densities (SEDs), as well as the resulting regions of tension and compression within the PDL and the surrounding bone were investigated during occlusion.

The results showed a distinct distribution pattern of high stresses and corresponding SEDs in the PDL and bone. Due to the tooth movement, peaks of SEDs were obtained in the PDL as well as in the bone on the labial and palatal/lingual sides of the alveolar crest. At the root, highest SEDs were detected in the PDL on the palatal/lingual side slightly occlusal of the root tip. This distribution pattern of high SEDs within the PDL coincides with the position of initial resorptive lesions in EOTRH affected teeth. The position of high SEDs in the bone can explain the typical age-related alteration of shape and angulation of equine incisors.

Introduction

Equine teeth are adapted to forage containing high levels of silica and subject to permanent dental wear inducing an age-related shortening. Due to the prolonged eruption, the clinical (erupted) crown maintains an almost constant length, the reserve crown (intra-alveolar part) however gradually shortens (Staszyk et al., 2006b). The intra-alveolar part of the tooth (reserve crown and root) serves as the attaching area of the periodontal ligament (PDL) which is known to be the most important tissue for the attenuation and conduction of masticatory forces (Staszyk and Gasse, 2005). Consequently, a shortening of the intra-alveolar parts of the tooth leads to a decrease in the PDL's attachment area, which causes an increase in the strains, stresses and strain energy densities (SEDs) in the remaining PDL. It is hypothesized that high stresses and SEDs cause local trauma such as fibre rupture and micronecrosis that may establish a suitable environment for microbiological settlement (Bender and Bender, 2003; Cordes et al., 2012a).

A reduction in the angle formed by the upper and lower incisors is accompanied by shortening of the incisor teeth (Habermehl, 1981; McMullan, 1983; Muylle, 2011). In young horses viewed in profile the upper and lower incisors stand almost in a straight line. Due to advanced wear, the cross-sectional shape of the dental crowns change and the angle formed by the incisors becomes increasingly acute in old horses (Muylle, 2011). The shortening of the incisor teeth, as well as the changing tooth position and angulation, affect the mechanical behaviour and load distribution of the PDL in older horses.

While the kinematics of the temporomandibular joint and the mandibular motion (Collinson, 1994; Baker and Easley, 2000; Bonin et al., 2006, 2007) and masticatory forces in equine cheek teeth (Staszyk et al., 2006a; Huthmann et al., 2009) are quite well understood, little is known about the masticatory forces in equine

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incisor teeth (Wallraff, 1942; Ritter, 1953), or the kinematics of incisor occlusion.

Interestingly, a disease recently termed equine odontoclastic tooth resorption and hypercementosis (EOTRH) affecting the incisor and canine teeth of aged horses has been clinically recognized (Staszyk et al., 2008). This painful disorder causes variable periodontitis with resorptive and proliferative alterations, initially starting in distinct areas along the lingual/palatal aspects of the incisors. The aetiology of this disorder is still unknown but it is considered to be a multifactorial disease and mechanical stresses in the PDL are assumed to represent an initiating factor (Staszyk et al., 2008). We hypothesize that distinct areas of the incisor PDL are subjected to local biomechanical overload causing focal periodontal disorders, which either become repaired, or alternatively initiate a cascade of cellular processes leading to EOTRH. Thus, we assume that a focal periodontal disorder is necessary for the onset of EOTRH.

In the first part of this study, we used the recently determined age-related and load-dependent Young's moduli of the PDL to simulate a physiological masticatory action (Schrock et al., 2013). The aim of this second part of our work was to investigate the resulting tooth movements and induced regions of high stresses, leading to high strains in the incisor's PDL. The SEDs in the PDL as well as in the surrounding bones were also examined. We aimed to draw conclusions on the age-related alterations of stressed regions in the PDL and in the jaw bones.

Materials and methods

Finite element (FE) analyses: Construction of 3-dimensional (3-D) models

The rostral aspects of upper and lower jaws of two horses (6 and 22 years old) were obtained. Using the same procedure as described in Part 1 (Schrock et al., 2013), cross-sectional images were generated by a micro-computed tomography (μCT) system (XTremeCT, Scanco Medical). Subsequently, 3-D models were constructed creating the tooth and the supporting bones uniformly and homogenously (Kawarizadeh et al., 2003) whilst paying great attention to constructing the PDL in a detailed and realistic manner.

Surface and tetrahedral volume meshes were generated out of the 3-D models as described by Lüpke et al. (2010) (Fig. 1). After net quality optimization, the meshes were transferred to the computer program COMSOL Multiphysics (version 4.3a, COMSOL) and the net quality was controlled as described in Schrock et al. (2013).

Table 1
Young's moduli and Poisson's ratios used for the finite element simulations.

	Young's modulus (MPa)	Poisson's ratio	
Tooth	20,000	0.3	Kawarizadeh et al. (2003), Cattaneo et al. (2005), Ziegler et al. (2005)
Bone	20,000	0.3	Abé et al. (1996), Vollmer et al. (2000)
PDL	1–8	0.45	Kawarizadeh et al. (2003), Schrock et al. (2013)

PDL, periodontal ligament; MPa, megapascals.

Determination of material parameters

The Young's modulus and the Poisson's ratio, values describing the material properties of tooth and bone, were taken from published values (Table 1) and were assumed to have linear elastic behaviour for the purposes of this study. As no literature exists on the Young's modulus of equine incisor's PDL, data were determined specifically by intrusive displacement experiments using 5 mm thick slice samples and FE calculations (Schrock et al., 2013). As an approach to the visco-elastic, non-linear behaviour of the PDL, the load-dependent, slice sample specific Young's modulus was used for the FE simulations of the corresponding teeth in the entire incisor arcades.

Validation

The experimentally determined intrusions of the slice samples were used to validate the complex 3-D models of the entire incisor arcades (Schrock et al., 2013). Therefore, the measured intrusions of the slice samples were compared with the calculated total displacements of the corresponding entire tooth. To simulate the intrusive displacement experiments the loading direction of the entire tooth was selected according to the loading direction of the slice samples. The resulting loading direction on the entire tooth was therefore along the longitudinal axis of its alveolus in an apical direction ('loading direction a)') (Fig. 2.1).

For each material used in the FE calculations, the boundary conditions had to be defined as either free (i.e. movable) or fixed (i.e. not movable). In this calculation the teeth and the PDL were defined as free, enabling displacements similar to the intrusive experiments. A fixation of the entire bone was chosen as a necessary physical requirement, as the embedding of the slice samples disabled any movement of the bone in the intrusive experiments.

The appropriate loading levels for the entire tooth are dependent on the ratio of the attaching areas between PDL and tooth, and between PDL and bone. As these attaching areas of the slice sample (5 mm thick) are only a fraction of the areas compared to the entire teeth (PDL attachment area of the young horse's root on a length of about 5.5 cm and of the old horse's root of about 3 cm length) the loading levels were selected in the same ratio as the slice sample's PDL and tooth's PDL

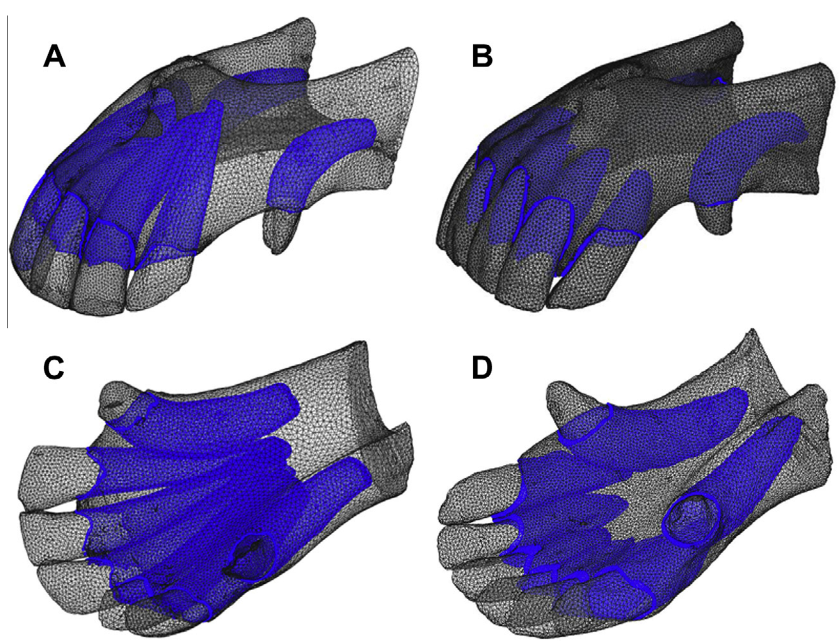

Fig. 1. 3-D tetrahedral volume meshes of the rostral aspects of an upper (A and B) and lower (C and D) jaw of a 6 year old horse (A and C) and a 22 year old horse (B and D). PDL is marked in blue.