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Finite element analysis of the equine periodontal ligament under masticatory loading

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Summary

The finite element method (FEM) is a highly approved method to simulate biophysical phenomena in computerized models of teeth and their periodontium. In human dentistry, the FEM has been used most fruitfully in the fields of restorative dentistry and prosthodontics. The introduction of FE-simulations in the field of equine dentistry requires a multiple step process which includes work from various disciplines.

Data sets from micro-computed tomography (µCT) were used for the 3-dimensional reconstruction of a computerized model of an equine mandibular molar together with its supporting tissues. Considering the distinct dental anatomy of the horse, special attention was paid to reconstruct individual, 3-dimensional models of each of the dental hard substances, the pulp cavities, the periodontal ligament and the alveolar bone. These models were assembled in a complete 3-dimensional model of the tooth and its surroundings. In a further step, volume models were generated and tooth movement during different masticatory actions (closing stroke, power stroke) was simulated by means of FEM. Boundary conditions for the masticatory actions were taken from previous force measurement experiments.

Masticatory loads caused a distinct spatial pattern of tensile and compressive stresses in the periodontal ligament. Visualization of von Mises stresses demonstrated stress concentrations in the vicinity of the delicate tips of the dental roots and in the subgingival area.

For the first time an FE-analysis was performed to analyze biomechanical effects in the equine periodontal ligament under masticatory loads. The elaborated FE-models will allow designing continuative clinical studies to analyze biomechanical effects also in the dental hard substances. Such studies will provide data to answer current questions in the fields of equine dental etiophatology, dental restorative therapies and prophylactic treatments.

Schlüsselwörter: Pferd, Ligamentum periodontale, Zähne, Finite Elemente Analyse, Pferdezahnheilkunde.

Zusammenfassung

Finite Elemente Analyse zur Berechnung von Kraftwirkungen im equinen Ligamentum periodontale während des Kauvorganges

Die Finite Elemente Analyse (FEA) wird als äußerst effektive und verlässliche Methode zur Simulation von biophysikalischen Prozessen im Zahn und seiner Umgebung, dem Parodontium, angesehen. In der Humanmedizin wird die FEA bereits seit längerer Zeit in den Fachbereichen der restaurativen Zahnheilkunde und der zahnärztlichen Prothetik eingesetzt. Die Nutzbarmachung der FEA für die equine Zahnheilkunde setzt zunächst die interdisziplinäre Erarbeitung von Grundlagen in einem mehrstufigen Arbeitsprozess voraus.

Aus Datensätze, die mittels Mikro-Computertomographie (µCT) generiert wurden, gelang die dreidimensionale Rekonstruktion eines mandibulären Backenzahns und seiner spezifischen Zahnumgebung. Um dem komplexen Aufbau der equinen Backenzähne gerecht zu werden, wurde besonderer Wert darauf gelegt, jede einzelne Hartsubstanz des Zahns sowie die Pulparäume, das Ligamentum periodontale und den Alveolarknochen jeweils als einzelnes dreidimensionales Computermodel zu konstruieren. Diese Modelle wurden dann virtuell zu dem eigentlichen Zahn und seiner Umgebung zusammengefügt. In einem weiteren Arbeitsschritt wurden Volumenmodelle erzeugt. Anschließend wurde die Bewegung und Belastung des Zahns während verschiedener Kauphasen (Kieferschluss, Mahlbewegung) mittels FEA simuliert. Die Formulierung biomechanischer Randbedingungen für die Simulationen erfolgte auf Grundlage bereits vorangegangener Studien zur Untersuchung der Kaukräfte des Pferdes.

Unter Einfluss der Kaukräfte entstand ein charakteristisches, räumliches Verteilungsmuster von Druck- und Zugspannungen im Ligamentum periodontale. Die Sichtbarmachung der von Mises Spannungen zeigte deutlich, dass Spannungen vermehrt in der Umgebung der Wurzelspitzen sowie in den subgingivalen Regionen auftreten.

Mit Hilfe der FE-Analyse konnten erstmalig biomechanische Effekte der Kaubewegung im equinen Ligamentum periodontale sichtbar gemacht werden. Die erarbeiteten FE-Modelle sollen in zukünftigen, klinisch orientierten Studien auch für die Analyse von Kaukraftwirkungen auf die Zahnhartsubstanzen genutzt werden. So soll geklärt werden, welche Rolle biomechanische Faktoren bei der Ent-

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Abbreviations: FE = finite element; FEM = finite element method; µCT = micro-computed tomography; PDL = periodontal ligament

stehung equiner Zahnerkrankungen spielen. Darüber hinaus wird nachfolgend erwartet, dass sich Empfehlungen für restaurative Therapien und prophylaktische Maßnahmen in der equinen Zahnheilkunde ableiten lassen.

Introduction

The finite element method (FEM) is considered to be an extremely useful tool to simulate the mechanical effects of chewing forces acting on the periodontal ligament and on the dental hard tissues (MACKERLE, 2004; WAKABAYASHI et al., 2008). This method allows the predicting and calculating of mechanical aspects of tissues and biomaterials which can hardly be accessed in vivo. Accordingly, the FEM has become a prevalent and fruitful method in the field of human dentistry including restorative dentistry, orthodontics, prosthodontics and oral mechanics (RICKS-WILLIAMSON et al., 1995; KATONA et al., 1996; TOPARLI et al., 2000; AUSIELLO et al., 2002). In order to establish modern therapeutic concepts (i.e. fillings of the infundibula, fillings of the endodontic cavities, treatment of periodontal diseases, rasping of the occlusal surfaces by use of motorized equipment) in equine dentistry, equine specific knowledge of the loading capacity and the resilience of the equine dental substances and the equine periodontal ligament is urgently needed. Further, data about equine chewing forces and their distribution within the dental arcades is expected to supplement recent studies which intend to develop new dental equipment like mouth specula (SIMHOFER and SCHRAMMEL, 2008). For that reason it is intended to utilize the FEM for equine dentition.

Imperative prerequisites for the suitable use of FEM are detailed 3-dimensional models of teeth and their surrounding tissues, generated finite element meshes, and knowledge of material properties (NATALI et al., 2004). In this regard, equine teeth are a particular challenge as their anatomic composition is far more complex compared to human teeth. Equine cheek teeth are classified as hypsodont teeth and are therefore completely different from the brachyodont teeth of dogs, cats and humans. Significant differences are found in terms of structure, profound age-related changes and a complex layering of the dental hard substances. The hypsodont equine cheek teeth are characterized by a deep folding of the hard substances at their sides (plissident body of the tooth). Additionally, maxillary cheek teeth possess deep enamel invaginations called infundibula which penetrate the occlusal surface. These characteristic morphologic features have to be considered in the production of 3-dimensional models and finite element meshes in order to allow reliable FE-simulations of equine cheek teeth and their periodontal ligament.

Material and methods

A promising approach to generate detailed 3-dimensional models of equine teeth and their surrounding structures is the use of micro-computed tomography (µCT). This non-destructive method provides data sets of high-resolution 2-dimensional images suitable for exact 3-dimensional reconstructions. Investigations were performed using an XtremeCT (Scanco Medical AG, Brüttisellen, Switzerland) with an isotropic spatial resolution of 41 µm. µCT-scans of a jaw section, containing a complete tooth (mandibular third premolar of a 9-year-old warm blood gelding) surrounded by an intact periodontal ligament fixed in 10 % neutral buffered formaldehyde solution were conducted. More than 2,000 2-dimensional µCT slices were obtained from the above-mentioned tooth to reconstruct individual, 3-dimensional models of each of the dental hard substances, the pulp cavities, the periodontal ligament and the surrounding bone. In a further step, these 3-dimensional models were assembled to a complete 3-dimensional model of the tooth together with its supporting tissues.

The 3-dimensional geometry for the tooth-model was generated with the program AMIRA (version 3.5, Visage Imaging GmbH, Berlin, Germany). Due to the small distance between consecutive images (41 µm) accurate 3-dimensional models of the external structure of the teeth could be provided (Fig. 1). As finite element analysis requires high processing power µCT-data were simplified in axial direction for modeling. Voxels were resampled to a size of 41 µm x 41 µm x 410 µm. A pivotal criterion for the exact 3-dimensional reconstruction of the complex arrangement of the individual layers of the tooth substances was the precise definition (segmentation) of each dental hard tissue and of the pulp cavities in all µCT-slices used for the reconstruction. As long as the individual dental substances (cementum, enamelum, dentin and pulp) were represented on the µCT-slices by different gray scale values based on Houndsfield units, as shown in Fig. 1, the segmentation could be achieved automatically.

Dentin and cement could not be distinguished with the help of Houndsfield units. In the area of the anatomical crown, these substances are spatially separated in the µCT slices by enamel; therefore the segmentation had to be accomplished semiautomatically. In the area of the anatomic roots, dentin and cementum are firmly attached to each other and could not be distinguished in the µCT slices. For those areas a homogenous material was modeled with the properties of dentin. This simplification should be acceptable because of the similar material properties of cement and dentin (Tab. 2).

The periodontal ligament was attached to the intraalveolar surface of the tooth following the deep folding at the sides of the tooth. It was created by a region growing algorithm from the external limitation of the tooth. According to the literature (STASZYK et al. 2006a; WARHONOWICZ et al., 2006) a mean thickness of 700 µm was assumed for the equine periodontal ligament (Fig. 1). Attached to the peripheral border of the periodontal ligament the alveolar bone was simulated by modeling a homogenous material (Fig. 1c). The ventral aspect of the mandible was assumed to be fixed for the calculations, i.e. in the computer model the mandible was assumed to be fixed while the maxilla was moving during masticatory action.

A surface model was produced from the segmentations of the µCT-slices. The surfaces of the above-mentioned

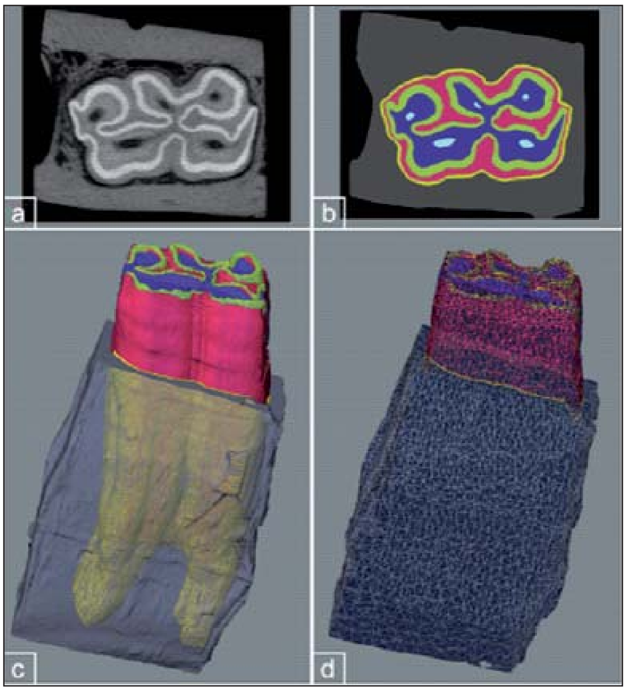

Fig. 1: a) Micro-CT image (horizontal section) of a right mandibular cheek tooth (third premolar, 9-year-old warm blood gelding); the dental substances are identified according to their representation in gray scales (Houndsfield units). b) The distinct outlines of the dental substances and the periodontal ligament were defined and labeled. Light blue: pulp; dark blue: dentin; green: enamelum; red: cementum; yellow: periodontal ligament; gray: bone. c) 3-dimensional surface model consisting of individual models of all dental substances, periodontal ligament and surrounding bone; d) 3-dimensional volume model consisting of individual FE-meshes of all dental substances, the periodontal ligament and the surrounding bone; total number of meshes: 70,608

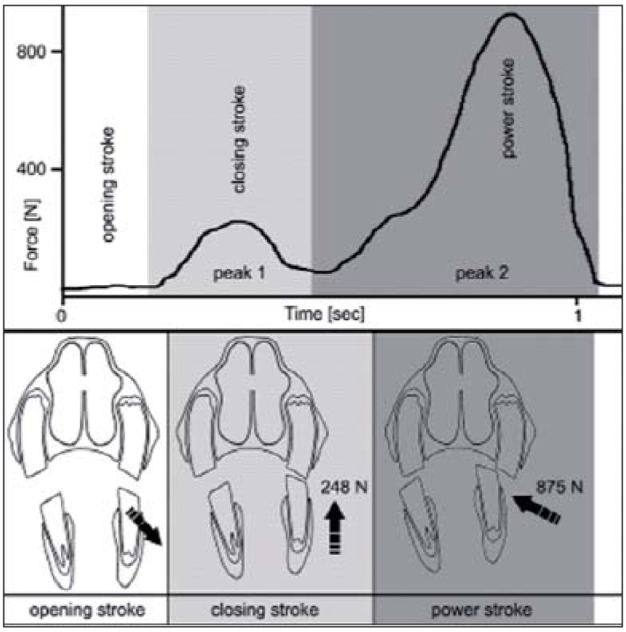

Fig. 2: Force-time diagram (top) and corresponding phases of the chewing cycle (bottom); the equine chewing cycle comprises three distinct phases:
- ● Phase 1 - opening stroke,
- ● Phase 2 - closing stroke,
- ● Phase 3 - power stroke, characterized by a vigorous movement of the jaw in a lingual direction. (From STASZYK et al., 2006b)

regions were calculated and described with triangles. The surfaces had to be strongly simplified before volume models were generated from these surfaces. Surface simplification was done by means of an edge collapse algorithm (internal function of the program AMIRA). Edges of the original surfaces were successively reduced to points, resulting in a reduced number of triangles and coarser surfaces. The shapes of the original surfaces were preserved by minimizing a certain error criterion (internal function of the program AMIRA). After this simplification the surfaces were optimized with regard to the quality of the triangles. Afterwards the volume model was generated. Thus, the volumes restricted by the surfaces were filled with tetrahedrons. Subsequently the quality of this mesh of tetrahedrons was optimized for the finite elements analysis. The mesh was exported and then used in the program COMSOL MULTIPHYSICS (version 3.5a, COMSOL AB, Stockholm, Sweden) for the finite elements analysis. Statistical data for the generated FE-meshes are given in Tab. 1. Appropriate material properties were derived from the literature and assigned to different regions (Tab. 2).

Boundary conditions

In a first approach the tooth movement during normal equine masticatory action was simulated with the FEM. Special attention was paid to the complex equine chewing cycle comprising 3 distinct phases (Fig 2). Regarding morphologic data and data from force measurement experiments (STASZYK et al., 2006b), 2 individual phases (a closing stroke and a power stroke) had been previously identified in which load is applied to the tooth (STASZYK et al., 2006b). During the closing stroke, load acts along the long axis of the tooth result in an intrusive movement. During the power stroke the load action comprises 2 components, an intrusive movement and additionally a sideward movement. Accordingly, it was necessary to perform 2 separate simulations, one for the closing stroke and one for the power stroke. The extent and direction of applied forces are listed in Tab. 3.

As the occlusal surface of equine cheek teeth possesses a distinct arrangement of pronounced enamel ridges, the force action was only applied to this area. The size of the enamel area had been calculated on the computerized 3-dimensional models using the area calculation feature of the AMIRA software.

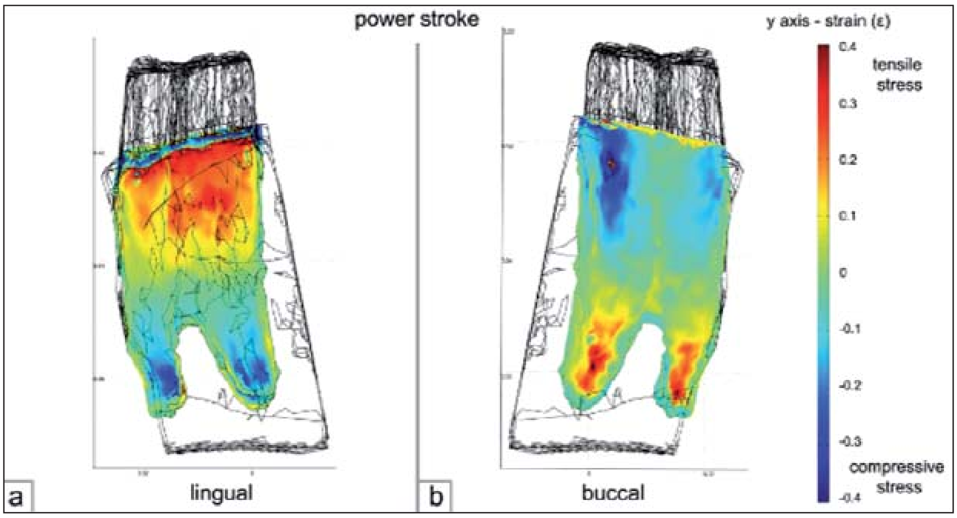

Fig. 3: Strain distribution in the periodontal ligament of a mandibular third premolar during the power stroke; a) lingual view; b) buccal view; compressive forces affect preferentially the occlusal half of the buccal side and the root segments of the lingual side. Tensile stresses occur predominantly in the occlusal half of the lingual side and in the root segments of the buccal side.

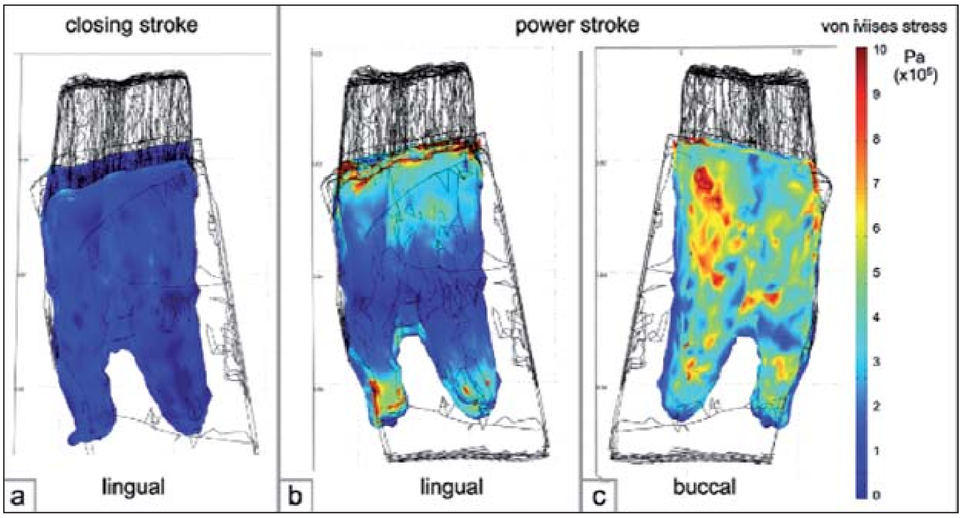

Fig. 4: Von Mises stress in the periodontal ligament of a mandibular third premolar; a) closing stroke, lingual view; b) power stroke lingual view; c) power stroke, buccal view; the periodontal ligament is subjected to extraordinary high stresses during the power stroke. Load concentrations are seen in periodontal areas next to the root tips and in subgingival areas.

The simulated tooth movements were used to calculate the mechanical effects, i.e. strain distribution and von Misses equivalent stress (a scalar stress value used to predict failure in engineering materials) on the periodontal ligament during the closing stroke and during the power stroke (Fig. 3 and 4).

Results

The simulated movement of the tooth during the closing stroke (vertical displacement) and during the power stroke (vertical and horizontal displacement) caused compressive and tensile stresses in the periodontal ligament. Compressive and tensile stresses were distributed in a distinct spatial pattern. Tensile stresses were predominately generated in the subgingival area of the lingual aspect of the tooth and next to the root tips of the buccal aspect of the tooth. Compressive stresses were arranged in an opposed spatial pattern. Relevant data is presented in Fig. 3.

The von Misses equivalent stress combines several stresses acting in a specified area resulting in normal stress. The visualization of von Misses stresses helps to identify those areas subjected to an extraordinary quantity of loads. These areas were identified adjacent to the tips of the roots and in the subgingival areas (Fig. 4).

Discussion

The simulation of the periodontal ligament has been based on the simplified assumption of uniform width of the periodontal ligament (700 µm) all along the intraalveolar part of the tooth. It should be noted that results from histologic investigations indicate that the equine periodontal space varies in its range along the tooth from 100 µm to 1,000 µm (STASZYK et al., 2006b; WARHONOWICZ et al., 2007). Furthermore, the equine periodontal ligament shows side-specific arrangements of the periodontal collagen fiber apparatus and the periodontal blood vascular system (STASZYK and GASSE, 2005). It has been hypothesized that those histomorphologic particularities are adapted to side-specific mechanical loads, i.e. compression or tension (STASZYK and GASSE, 2005). Therefore, it might be necessary to model the periodontal ligament in a more precise manner. Nevertheless, the used reconstruction (a constant thickness of the periodontal ligament) has been widely used for successful FE-simulations for brachyodont teeth (TOMS and EBERHARDT, 2003; NATALI et al., 2004; CATTANEO et al., 2005; ONA WAKABAYASHI, 2006; WAKABAYASHI et al., 2008). The FE-analyzes were performed assuming a linear stress-strain relationship for the periodontal ligament. By contrast, in recent studies the assumption of a non-linear or a bi-linear E-modulus for the

Tab. 1: FE-mesh statistics

Material	Mesh elements
Bone	15,542
PDL	8,682
Pulpa	5,022
Enamel	13,433
Dentin	19,139
Cement	8,790
Sum	70,608

Tab. 3: Loading and boundary conditions for the simulation of the tooth movement during the closing stroke and the power stroke

	Closing stroke	Power stroke
Force (x-axis)	-	-
Force (y-axis)	-	3.7 MPa
Force (z-axis)	2 MPa	6.5 MPa
Enamel cross section area	133 mm²	133 mm²

Tab. 2: Material properties

Material	Youngs modulus (MPa)	Poissons ratio	Reference
Bone[1]	12,200	0.3	CATTANEO et al., 2005
PDL	2	0.45	estimated, based on MIDDLETON et al., 1996
Pulp	2	0.45	MIDDLETON et al., 1996
Enamel	84,100	0.2	MIDDLETON et al., 1996
Dentin	18,600	0.31	MIDDLETON et al., 1996
Cement	15,000	0.3	SHAW et al., 2004

[1] Mean value for full cortical bone, partly cortical bone and bone marrow

periodontal ligament has been favoured in order to gain most precise results from FE-simulations (TOMS and EBERHARDT, 2003; ZIEGLER et al., 2005; WAKABAYASHI et al., 2008). However, these techniques have been applied to FE-models of simple brachyodont teeth which are moved along the long axis of the tooth. Applying a non-linear or bi-linear E-modulus to the complex equine tooth requires extensive adjustments in the FE-simulation. This will be a subject for further investigations.

The von Misses equivalent stress combines several stresses acting in a specified area resulting in normal stress (AMARANTE et al., 2008). Thus, the visualization of von Misses stresses helps to identify those areas in the periodontal ligament in which loads are concentrated (AMARANTE et al., 2008). Using this method, extraordinary loads were detected in distinct areas of the periodontal ligament, i.e. in areas surrounding the root tips and in subgingival areas. This spatial pattern coincides with the location of typical equine dental/periodontal disorders. Periapical infections are frequently seen in equine cheek teeth and are a major cause of dental extractions (DACRE et al., 2008; CARMALT and BARBER, 2004). Although great efforts have been undertaken to identify predisposing factors for such a disease a consistent explanation for the etiophatology has not been presented up until now (DIXON and DACRE, 2005). The recognition of high mechanical loads in the periapical area by means of our FE-simulations might contribute to clarifying some of the predisposing factors. Although the used linear E-modulus for the periodontal ligament might cause imprecise results, it should be emphasized that calculated von Mises stresses around the root tips are obviously underestimated when using a linear E-modulus for the periodontal ligament (DURKEE et al., 1998; TOMS and EBERHARDT, 2003). Thus, the von Mises stresses around the root tips are expected to be even higher than those calculated in the present study. Similar considerations as for the periapical infections apply to equine periodontal diseases along with deep periodontal pocket formation. As shown in the FE-simulations the subgingival areas of the periodontal ligament are subject to high amounts of mechanical loads. These results prove the assumption that mechanical loading is a predisposing factor for periodontal diseases (DIXON and DACRE, 2005; KLUGH, 2005). Additionally, the FEM provides a tool for simulation situations of malocclusion and their influence on the mechanical loading of the periodontal ligament. It is expected that results from these intended studies will serve to elaborate new prophylactic and therapeutic treatments for equine periodontal diseases.

Generating computerized 3-dimensional models of each individual dental substance facilitated calculation of morphometrical data which can hardly be acquired in original teeth. For example, the size of the load-bearing enamel ridges of the occlusal surface could be recorded. Such data will serve to supplement data which has already derived from chewing force experiments. Hitherto, the forces (in Newton [N]) arising during the masticatory action had been measured and calculated (STASZYK et al., 2006b; HUTHMANN et al., 2008, 2009). However, the impact of compression strength (in Pascal [Pa]) on the occlusal surface remained unknown due to the lack of data for the actual contact area of the tooth. First results indicate that the compression strength on the enamel ridges is in the range of several Mega Pascal [MPa], which was predicted by HUTHMANN et al. (2009).

Conclusions and future prospects

For the first time an FE-model has been developed to analyze biomechanical effects of masticatory loads in the equine periodontal ligament under physiologic conditions. The elaborated FE-models may allow designing continuative clinical studies to analyze biomechanical effects also in the dental hard substances receiving masticatory loads.

The biomechanical data yielded from such FE-simulations might provide needed data:

- to reconsider and improve techniques and procedures in routine equine dentistry, i.e. the reduction of focal dental overgrowth,
- to identify predisposing factors for biomechanical disorders in the dentition (teeth and periodontium) and in the temporomandibular joint,
- to select filling materials according to required biomechanical properties,
- to develop instruments for advanced dental procedures and
- to plan procedures for stabilizing teeth by filling necrotic pulp horns and/or carious infundibula.

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