Comparison of Stress Zones in Finite Element Models of Deformed Bovine Claw Capsules

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ABSTRACT

Pathological claw formations occur subsequent to irregular or prolonged claw trimming periods and as a result of improper flooring. Clinical experience and material testing finds horn of minor quality to be associated with the malformations. Finite element models (FEM) of a flat claw (FC), a contracted claw (CC), and a laminitic claw (LC) were designed from native claw specimens to combine material properties and altered claw geometry for stress analysis. The FEM were created by digitizing the typically deformed exungulated claw capsule by means of computed tomography or digital photography. The derived geometry data were meshed with finite elements and the material properties were attributed. Loading was performed via vertical load vectors according to the suspensory and support apparatus of the bovine digit. All FEM were loaded on soft floors. Loading of the FEM of the FC with 756 N exhibited maximum stress values of 3.32 MPa in the dorsal wall, that of the CC exhibited comparably lower stress of 1.33 MPa in the distal abaxial wall, and the model of the LC showed maximum stress of 4.51 MPa in the region of the dorsal border, all at the same loading. The solar surfaces and the corresponding imprints showed stress concentrations in the palmar aspect of the bulb in the FC, a highly stressed bearing margin of the abaxial wall in the CC, and a diffusely stressed sole and bulb in the LC in contrast to the sound claw models. The FEM of the selected pathological claw forms (FC, CC, LC) calculated high stress zones exactly at locations in the claw wall and sole where clinical experts expect the typical claw lesions for these pathologies. These results were obtained simply by exchanging the outer form of the claw capsules; the method of loading and type of flooring for these pathological models were equivalent to those of the sound FEM. It is highly possible that the stress zones derived from these calcu-

lations represent corium compression in reality, and these data support the pathophysiological theory that claw lesions may arise as a consequence thereof.

Key words: finite element analysis, claw capsule deformities, material stress

INTRODUCTION

Pathological conditions affecting the distal region of the bovine limb include infectious diseases and claw lesions associated with major systemic diseases (Bergsten, 1997). Prolonged trimming intervals and malformed horn capsules can induce pain in the claw (Kloostermann, 1997), deterioration of claw horn (Hinterhofer et al., 2006a), and subsequent lameness. Functional claw trimming (Toussaint-Raven et al., 1985) was introduced to reduce the onset of malformations and to minimize their consequences (Lischer and Ossent, 2001). There have been few objective investigations of claw deformities (Greenough et al., 1990; Kloostermann, 1997), with only the corkscrew claw, the slipper foot, and the beak claw being named conditions. Comprehensive descriptions of these and other conditions are available in the German literature (Dietz and Prietz, 1982; Stanek and Fessler, 1982), but how malformed capsules deform and how they compress and irritate the underlying dermis have not been investigated, and can only be estimated based on clinical experience. For the present study the classes of the flat claw, the contracted claw as the preliminary stage to the corkscrew claw, and the chronic laminitic claw were selected. Although the malformations associated with these claw shapes may not cause lameness, the shapes are related to an increased risk for specific claw lesions that may then be followed by lameness. Specific interest was focused on selecting the best possible specimens that would most closely represent the chosen pathologies. Furthermore, it was important to transform claw geometries into digitized images. The finite element models (FEM) of the digitized claws were used to pinpoint stress zones derived from the specific claw forms and their possible relation to claw lesions.

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Finite element analysis (**FEA**) is a computer-based technique for the determination of stress, strain, and other mechanical traits of structural components. Finite element analysis has proven itself as an essential tool in practically all areas of science, in particular structural and mechanical engineering. In medical science the main contribution of FEA is that it can offer detailed insights into the mechanical properties and dynamic behavior of tissue, organs, and bones without having to resort to actual experiments with real samples. Finite element analysis has been applied to humans (Beillas et al., 2004; Cheung and Zhang, 2006), horses (Hinterhofer et al., 2001; McClinchey et al., 2003), donkeys (Newlyn et al., 1998), and cattle (Wagner, 2004; Hinterhofer et al., 2005b). The human studies concentrated on stress in bones and joint behavior and their relation to load or wearing shoes. The veterinary studies determined stress and strain in the specific hoof capsules as a result of loading and different floorings. The FEM of the sound bovine claw capsule (Hinterhofer et al., 2005b) calculated a relatively high stress zone only in the proximal axial wall on soft flooring; the footprint on the floor had the claw-like appearance seen in pressure plate results and in claw imprints in muddy floors.

Applying FEA to biogenic structures requires accurate data on the material properties of the components of interest, precise image digitization, and well-surveyed loading and boundary conditions. Substantial data are available on the structural characteristics (Mülling et al., 1994; Vermunt and Greenough, 1995) and material properties (Baillie et al., 2000; Franck et al., 2006; Hinterhofer et al., 2005a) of the bovine claw, and an FEM of the bovine claw capsule was used to predict the influence of floor type on stress and strain induced in the claw horn (Hinterhofer et al., 2006b). Yet, because no FEM of a deformed bovine claw capsule has been reported, the present study applied FEA to malformed bovine claws to improve the understanding of the biomechanical reactions of capsules to the altered geometry and of the onset of pathological processes in the dermis.

MATERIALS AND METHODS

Sample Selection

A flat claw (**FC**) from a front leg, a contracted claw (**CC**), and a claw affected with the changes of chronic laminitis (**LC**) both from hind legs were chosen from Austrian Fleckvieh cows slaughtered for reasons other than for the purpose of this study. The 3 claws were chosen from hundreds of specimens to represent the typical pathological deformation as described below. Because only 3 claws could be used for the specific digiti-

Figure 1. Illustration of a typical flat front claw (FC) and drafted foot, exhibiting a pointed apex, long dorsal wall, flat and square sole, and subtle superficial grooving of the axial wall: a) dorsolateral view; b) axial and distal view. The FC for image digitization had the following dimensions: dorsal border = 101 mm; heel depth = 39 mm; diagonal = 156 mm; and hoof angle = 41°.

zation, the variations in shape that could possibly occur within the bovine species around the world had to be neglected. The claw capsules were disengaged from the dermis after soaking for 20 h in 60°C water. The capsules were carefully air dried and scanned to obtain the geometrical data needed for the FEM.

Figure 1 shows a typical FC, which was a long medial front claw exhibiting narrow superficial grooves, especially in the axial wall, and with a straight dorsal border. The axial excavation was very flat and the sole was approximately rectangular. The sole and the hard and soft bulb were overgrown and rather thick.

Figure 2 shows a typical CC, which was a narrow and bent lateral hind claw, with the abaxial wall growing bow-like beneath the sole, displacing the latter in the dorsal direction. The apex of the claw was pointed

Figure 2. Illustration of a typical contracted lateral hind claw (CC) and drafted foot. The dorsal margin is curved, the tip of the toe is beaked and bend toward the foot axis, the abaxial wall grows bowl-like toward the foot axis, and the axial wall exhibits upwardly tilted grooves: a) dorsolateral view; b) axial and distal view. The CC for image digitization had the following dimensions: dorsal border = 93 mm; heel depth = 50 mm; diagonal = 154 mm; and hoof angle = 53°.

and slightly twisted, and the dorsal border was curved. The axial wall was grooved and tilted upwards.

Figure 3 shows a typical LC, which exhibited a concave dorsal wall with partial heavy horizontal grooving. The grooves diverged at the heel and the walls appeared dull. The sole showed diffuse hemorrhaging.

Creation of an FEM

Any FEM is based on the precise capture of the inside and outside surface data of the structure desired, followed by the meshing of the geometry with finite ele-

Figure 3. Illustration of a typical lateral hind claw affected with the changes of chronic laminitic claw (CL). The dorsal wall is concave and contains isolated heavy grooves, which diverge at the heels. The quality of the claw horn is low, with no shine in the horn wall: a) dorsolateral view; b) axial and distal view. The LC for image digitization had the following dimensions: dorsal border = 85 mm; heel depth = 30 mm; diagonal = 148.5 mm; and hoof angle = 47°.

ments (FE). Finite elements are small geometrical components defined by the coordinates of their corner nodes and act as a 3-dimensional (3D) puzzle, making the structure calculable in its every detail. The FE are assigned the material properties of the structure of interest, namely the modulus of elasticity (E), a material constant defining the material's resistance against deformation, the Poisson ratio (ν), and the material's physical reaction to force (isotropy, anisotropy, or orthotropy). Loading of an FEM must be defined by vectors. The type of floor on which the models will be loaded can be defined as a separate FEM, as was done for this study. Among a variety of possible FEA results, we

Table 1. Finite element (FE) mesh criteria of the finite element models of the flat claw (FC), contracted claw (CC), and laminitic claw (LC) including the element length of the FE, the total number of FE, the number of nodes used for the FE, and the material properties¹ of the claw capsule

Criterion	Finite element model		
	FC	CC	LC
Global element length, mm	2.1	2.1	2.2
FE, n	62,750	92,925	59,455
Nodes, n	104,660	22,090	98,600
<i>E</i> of wall, MPa	400 to 200	300 to 150	450 to 200
<i>E</i> of sole, MPa	140	70	100
ν	0.3	0.3	0.3
Orientation	Isotropic	Isotropic	Isotropic
Loading, N	756	756	756

¹*E* = modulus of elasticity; ν = Poisson's ratio.

chose the von Mises stress for the bovine claw horn, which includes all directions of stress in the material and combines them in a single, comparative stress value (Rumpel and Sondershausen, 1990). The outcome of any FEA is a calculated result, expressed by numbers in megaPascals, which may also be represented as colored figures.

Digitizing the Geometrical Data. The FC and CC were scanned at the Upper Austrian University of Applied Sciences (Wels, Austria) by a 3D computed tomography (CT) scanner (RayScan, Walischmiller, Germany). The CT data were obtained at a resolution of 115.3 μm using a 1-mm aluminum prefilter, with each 360° rotation comprising 900 projections. The reconstructed data were converted into a 3D computer-aided design model, which was transferred to the Austrian Research Institute for Chemistry and Technology (Vienna, Austria), where the FEM was constructed by meshing the geometry using standard software (IDEAS, 10 NX series SDRC, Electronic Data Systems, Plano, TX). The LC was scanned using an optical 3D scanner (Westcam, Mils, Austria), with 2 cameras taking pictures in 45° increments of a projected black striped pattern. A total of 24 images were taken in the 3D planes, with 1.3 points of measurement used to calculate the 3D coordinates of the claw capsule. The data were then integrated into a full volume model using computer-aided design software at the Austrian Research Institute for Chemistry and Technology.

Meshing, Material Properties, and Loading of FEM. The outline geometry was meshed with FE in 3 dimensions to allow the volume data to be transformed into a FE mesh, based on the following criteria (Table 1): basic element size of the FE, number of FE, number of nodes of the FE, *E*, ν , and the material orientations.

The 3 FEM were assigned different *E* values according to previous investigations by our group (Hinterhofer et al., 2006a). To realistically simulate measured *E* values in the claw walls, the dorsal region was always

assigned the highest *E* values, and it dropped smoothly to the specific *E* value of the bulbar region (Figure 4).

The FEM were loaded using oriented force vectors that were distributed equally on the inside surfaces of FE of the claw wall (70%), according to the pattern of the suspensory apparatus (Maierl, 2004), and on the sole (30%). The total load applied to each FEM was 756 N, representing the weight borne by 1 claw (the fictitious animal was assumed to have a BW of approximately 600 kg). The platforms (floors) supporting the FEM were simulated as flat and even planes with the material properties of a rubber mat (*E* = 5 MPa; ν = 0.35; static friction μ = 0.6). When a claw was loaded, it met the floor in a static quasi-landing manner, and hence the imprint of the FEM was determined by the geometry of the claw and the landing procedure.

Survey of Results. Among the wide variety of expressible FEA data, we selected the von Mises stress (MPa) of the material. Von Mises values were determined by the standard equation $\zeta = \frac{1}{\sqrt{2}}$

$\sqrt{(\zeta_1 - \zeta_2)^2 + (\zeta_2 - \zeta_3)^2 + (\zeta_3 - \zeta_1)^2}$, where ζ in the von Mises stress, and ζ_1 , ζ_2 , and ζ_3 are the maximal principal stresses in the orientations of the 3 coordinates (Rumpel and Sondershausen, 1990). For better comparison between the models, several single values in the FEM (Figure 5) and at the floors (shown in the figures) are listed in Table 2. Stress and strain values in FEM are usually presented by displaying colored figures of the respective model, examples of which are displayed in Figures 6, 7, 8, and 9. Such figures provide a good overall comprehension of the mechanical consequences of the loading.

RESULTS

General Descriptions and Features of the FEM

Points of stress in the FE-claw capsules as a result of the loading and the FEM shape were calculated by

Figure 4. Solid unloaded finite element models of a laminitic claw (left), a contracted claw (middle), and a flat claw (right). Colors represent the modulus of elasticity assigned to the various segments according to the scales in the images. Color images are available online at <http://jds.fass.org/vol90/issue8/>.

the software. They are described as areas of stress, stress points, connective stress paths, and stress patterns; the stress in the afflicted area and the pinpointed location is measured in megaPascals.

The FEM of the FC (FEM-FC) exhibited a maximum von Mises stress of 3.32 MPa at the inner surface of the claw capsule at the transition between the axial and dorsal walls (Figure 6). This area was surrounded by a stress path pulling predominantly to the abaxial wall that exhibited values from 1.5 to 2.66 MPa. A stress band also ran along the junction of the sole and the abaxial wall inside the distal abaxial wall, again with values from 1.5 to 2.66 MPa. The outer surface of the proximal dorsal wall showed a diffusely distributed stress pattern, with no stress at the tip of the claw. The axial wall exhibited moderate stress (0.9 to 1.5 MPa), and the heel exhibited low stress (≤ 0.6 MPa). Within the solar surface, the axial part of the hard bulb at the transition to the soft bulb exhibited stress of 0.43 to 0.91 MPa. The main part of the hard bulb exhibited stress of 0.5 to 0.7 MPa, and the heels and the tip of the sole were not stressed (≤ 0.2 MPa). When touching the floor, the FEM-FC showed a slight displacement in the palmar direction, but no tilting was detected when viewed from behind.

The FEM of the CC (FEM-CC) exhibited a maximum stress of 1.33 MPa at the inside surface of the claw wall, with a distinct and impressive stress patch at the distal abaxial wall close to the transition to the sole (Figure 7). The maximum stress was only 0.99 MPa outside the same region. The dorsal wall exhibited a band-like stress field, abaxial to the dorsal border in the range 0.26 to 0.59 MPa and equally for the inner and outer surfaces. The maximum stress at the axial wall was only 0.46 MPa, and the heels were not stressed. The solar surface showed a band-like stress concentration along the junction to the abaxial wall in the range 0.53 to 1.06 MPa, with the stress being low

in the remainder of the digit pad (≤ 0.2 MPa). The FEM-CC tilted outwards when touching the ground, around the center of the distal abaxial wall. The imprint therefore reflects the geometry of the solar surface in this slightly oblique landing position.

The FEM of the LC (FEM-LC) exhibited a maximum stress of 4.51 MPa at both the inside and outside of the horn of the dorsal border (Figure 8). The stress in the dorsal wall was from 1.35 to 3.38 MPa, with 2 peaks: one in the grooved dorsal border and one at the junction to the abaxial sole. Stress in the axial wall was also high, presenting as a stress patch in the plantar axial wall (1.35 to 1.8 MPa), with low stress in the heels (≤ 1 MPa). The solar surface exhibited a diffuse stress distribution along the distal rim of all of the claw wall segments and over most of the hard bulb (ranging from 0.9 to 2.03 MPa). The FEM-LC showed the lowest tendency to tilt inwards around the distal rim of the axial wall, but the entire sole was in contact with the ground, leaving a depression there.

Features of the FEM Floors

For the FEM-FC, the floor showed the imprint of the rectangular sole and the smaller heel (Figure 9). The weight was almost evenly distributed, with the stress ranging from 0.1 to 0.3 MPa. A large peak was found in the area where the soft bulb and the heel transmitted force to the platform. For the FEM-CC, the floor had an imprint only underneath the abaxial wall and the adjacent sole, with a large peak reaching 0.45 MPa. The floor supporting the FEM-LC exhibited diffuse impressions of the large parts of the sole and the bulb, with stress peaks disseminated over the imprint (0.3 to 0.6 MPa).

Figure 5. Illustration of positions in the finite element models (FEM) form where stress data were surveyed using software. The size of the pattern was normalized to account for the variations in the sizes of the respective FEM.

DISCUSSION

Formation of Altered Claw Shapes

Claw soundness has always been a major point of concern for all who deal with cattle. Sound claws are mostly correlated to regular claw formation based on the theory that an even distribution of stress is most important in maintaining claw health. Altered claw shapes, such as the FC and CC, although reduced by

breeding selection, may occur when claw trimming periods are exceeded or when altered loading situations in the limb provoke uneven horn growth. When dealing with the LC, the chronic laminitis syndrome precedes the altered claw capsule (Greenough et al., 1990). All 3 claw formations may not be the cause for lameness. But in the clinic, there is a higher incidence of horn lesions in the bulb and sole when dealing with a wide, flat claw (Kloostermann, 1997). The contracted form seems to first disturb blood circulation in the distal abaxial wall, leading to distal wall necrosis and white line disease in the abaxial segment; and the laminitic process results in an increase of pressure under the distal phalanx, possibly leading to diffuse hemorrhaging in the sole horn. With the help of FEA, we wanted to improve the understanding of the biomechanics of pathological claw forms and find the mechanical influences in the development of horn lesions subsequent to these alterations.

FEA

The altered geometries of the FC, CC, and LC calculated stress accumulations where the clinician would expect the typical claw lesions, while maintaining the same loading conditions as for the sound claw model. Finite element analysis has been applied in veterinary science to predict the influences of farriery and flooring on the horse hoof (Hinterhofer et al., 2001; McClinchey et al., 2003) and the bovine claw (Wagner, 2004; Hinterhofer et al., 2006b). The construction and analysis of FEM of diseased and deformed claw capsules improves our understanding of the biomechanical influences of the altered geometry. The FEM of the sound claw (Hinterhofer et al., 2005b) calculated a claw-like imprint in the support platform and almost evenly distributed stress around the weight-bearing rim of the distal claw wall.

Selection of Specimens

The specific CC capsule shown in Figure 2 was decided upon because the abaxial wall was weight bearing; the rest of the claw was clearly contracted and mutated. Compact claws with lesser modifications appeared close to a slightly overgrown narrow claw. Moreover, more heavily contracted and contorted claws could have produced spurious results for the impressions on the platform. Our selected form of FC (Figure 1) was broadly consistent with the above-described form, although the thickness of the sole did not coincide with some reports (Dietz and Prietz, 1982; Stanek and Fessler, 1982). The available FC samples (rectangular sole, pointed toe angle, and under-run heel) exhibited rather thick soles toward the claw tip (Toussaint-Raven et al.,

Table 2. Stress values (MPa) of outside surface of finite element models (FEM) of a flat claw (FC), a compact claw (CC), and a laminitic claw (LC) educed at selected positions to enable comparison between the 3 FEM¹

Model claw	Abaxial wall position																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
FC	1.83	1.66	1.33	0.49	0.16	1.16	0.66	0.99	0.49	0.16	0.33	0.49	0.99	0.33	0.33	0.16	0.66	0.16	0.16	0.33
CC	0.26	0.39	0.59	0.46	0.19	0.26	0.46	0.46	0.26	0.26	0.13	0.26	0.33	0.39	0.33	0.19	0.46	0.13	0.13	0.13
LC	2.03	1.80	2.48	2.48	0.90	1.35	1.80	2.03	2.25	3.38	1.13	1.13	1.35	0.90	1.13	0.67	0.90	0.45	0.22	0.22
	Axial wall position																			
	21	22	23	24	25	26	27	28	29	30	31	32	33	34						
FC	2.16	1.33	0.66	0.16	0.16	0.49	0.33	0.66	1.16	0.99	0.66	0.83	0.33	0.49						
CC	0.06	0.33	0.46	0.13	0.06	0.26	0.19	0.13	0.39	0.13	0.19	0.19	0.06	0.06						
LC	2.93	3.15	1.13	0.45	1.35	0.67	0.90	1.80	1.58	1.35	1.80	1.58	0.67	0.22						
	Sole and digital pad position																			
	35	36	37	38	39	40	41	42	43	44	45	46	47	48						
FC	0.06	0.61	0.85	0.55	0.85	0.18	0.43	0.61	0.43	0.91	0.24	0.55	0.55	0.31						
CC	0.06	0.19	0.19	0.25	0.25	0.06	0.19	0.26	0.26	0.66	0.66	0.53	1.06	0.66						
LC	0.45	1.58	0.90	0.45	1.35	1.58	1.35	1.58	1.58	0.45	2.03	1.80	1.13	0.90						

¹Positions 1 to 20 describe the abaxial and dorsal wall, 21 to 34 the axial wall, and 35 to 48 the solar surface (Figure 5).

1985). The preparation of the deformed claw capsules before digitization concentrated on the creation of an even and smooth solar surface while maintaining the majority of the pathological deformities.

Digitizing the Geometrical Data

Both methods used to digitize the geometrical data, optical for the LC capsule and CT for the FC and CC, were equally suitable for creating the FEM in IDEAS.

Loading of the FEM

The FEM of the 3 claw capsules was loaded in accordance with the assumed load distribution on the suspensory apparatus (Maierl, 2004). Consistent with the connective fibers that bond the distal phalanx to its horn capsule, vertical vectors were defined as pulling at the inside surface of the dorsal and abaxial claw wall (70% of the load). In addition, vectors transmitted pressure

Figure 6. Stress in a finite element model of a flat claw subject to a 756-N load on a soft platform: a) axial aspect, b) abaxial aspect, c) solar surface, d) inner aspect of the dorsal wall, e) inner aspect of the lateral wall, and f) outer aspect of the dorsal wall. Color images are available online at <http://jds.fass.org/vol90/issue8/>.

Figure 7. Stress in a finite element model of a contracted claw subject to a 756-N load on a soft platform: a) axial aspect, b) abaxial aspect, c) solar surface, d) inner aspect of the lateral wall, e) inner aspect of the dorsal wall, and f) outer aspect of the dorsal wall. Color images are available online at <http://jds.fass.org/vol90/issue8/>.

to the solar horn underneath the distal phalanx (30% of the load). The total load was predefined as 750 N, corresponding to 25% of the BW of an average Fleckvieh cow; the area-related vector distribution resulted in a final load of 756 N per claw capsule. Although the weight of a real animal may be distributed unevenly between the hind and fore feet, all FEM (deformed and sound) were loaded with the same load to facilitate comparisons. Also, we defined isotropy for all of the material, allowing

linear calculations. It should be noted that conclusions can be easily drawn for higher or lower BW.

Results and Comparison Among FEM and Relation to Clinical Findings

In the FEM-FC, the majority of the proximal and middle part of the dorsal wall was highly stressed both inside and outside (Figure 6). This can be attributed to the

Figure 8. Stress in a finite element model of a laminitic claw subject to a 756-N load on a soft platform: a) axial aspect, b) abaxial aspect, c) solar surface, d) inner aspect of the dorsal wall, e) inner aspect of the lateral wall, and f) outer aspect of the dorsal wall. Color images are available online at <http://jds.fass.org/vol90/issue8/>.

Figure 9. Claw imprints showing stress on the floors for the finite element models of a flat (FC), a contracted (CC), and a laminitic claw (LC). Color images are available online at <http://jds.fass.org/vol90/issue8/>.

backwards-tilted distal phalanx caused by the pointed toe angle and the subsequently altered tension on the suspensory apparatus. The discrete and superficial grooves often found with this claw form may represent a reaction to this stress distribution, although the relatively unstressed periople is not consistent with this. The stress peak at the inside of the dorsal claw wall at the transition to the axial wall (which appears bright in Figure 6) is not yet explainable. It appeared exactly at the beginning of the wall segment, inside the dorsal border of the claw. Numerical artifacts can be excluded because the inside of the claw wall is edge free and the load vectors are distributed evenly. The stress band at the inside of the abaxial wall at the transition to the sole may be due to the same mechanism as the stressed dorsal wall; that is, the spreading and separation of the white line often found in this claw form. The maximum stress in the digital pad of the FEM-FC occurred at the axial and palmar hard bulb toward the soft bulb, which was distant from the applied loading. Most of the typical sole lesions are found in this region of maximum stress, even in well-maintained claws (Mülling, 2004).

The FEM-CC showed a similar but more comminuted stress pattern in the dorsal wall relative to the FEM-FC. The maximum mean stress was only 0.59 MPa, whereas the same region in the FEM-CC showed values up to 1.83 MPa. Although loaded in exactly the same way as the other models, the remainder of the claw capsule exhibited a stress pattern that could explain the undesirable complication of the CC formation: necrosis of the distal abaxial margin of the distal phalanx due to high stress along the inside of the distal abaxial wall. The wall in its bent form curves under the sole and compresses the underlying horn and soft tissues. Compression and malnutrition leads to necrosis and the pathological deformation of the distal margin of the bone.

Also, the adjacent part of the sole and the digit pad exhibited stress up to 1.06 MPa.

The FEM-LC exhibited the highest stress values among the 3 FEM, peaking at the grooved dorsal wall and at the inside of the dorsal border (to 2.48 MPa). The altered tension due to the deteriorated suspensory apparatus may account for this phenomenon. The stress peak in the periople was attributable to the dried horn capsule. All segments of the claw wall exhibited stress greater than that in the other FEM, and the stress pattern extended to the distal abaxial wall and to a stress band parallel to the dorsal border in the axial wall. Furthermore, the plantar part of the axial wall was highly stressed. The sole and the digit pad exhibited high stress along the distal rim of the claw wall and a diffuse stress pattern along the center of the solar surface. The laminitic process appeared to widen the loaded and depressed portions of the sole and, at the same time, stress the material of the claw wall. Scattered hemorrhages in the horn of the digit pad, which often occur as a side effect of the laminitic pathology, showed a similar distribution. Again, the stress was relatively low in the tip of the toe and the heels for this loading position.

Supporting Platforms and Imprints Therein

The floors of the respective FEM showed imprints of the solar surface, including the distal rim of the wall sections, the anatomical sole, and the hard and soft bulb (Figure 9). Despite the equal loading applied to the 3 FEM, the model claws met the surfaces of the floors in different ways: the FEM-FC tilted backwards slightly, aggravating the concentration of stress in the palmar aspect of the digit pad; the FEM-CC rotated outwards around the bended and highly stressed abaxial wall; and the FEM-LC tilted inwards only slightly to leave most

of the load on the digit pad. It should be noted that simulating the floors as rubber mats resulted in stress and strain in the materials that were lower than if hard floors had been used. Comparisons with experimental force-plate (Scott, 1988) and pressure-plate (van der Tol et al., 2002; Franck and De Belie, 2006) data revealed that the stress values obtained in the present study were within realistic ranges. Future studies should extend these results by investigating dynamic loading and landings.

CONCLUSIONS

Finite element analysis represents a very precise and revealing tool in veterinary science, particularly for stress analysis of bovine claw capsules. The hypothesis that the altered geometry of the deformed claw capsules may induce claw pathologies, such as ulcers and compression necrosis of the lamina with the potential of subsequent infections, finds its calculative proof in the stress results of the FEM of the FC, CC, and LC. Although validation of the FEM is only possible via clinical observations, our results justify the conclusion that prevention of claw deformities by means of breeding selection, proper flooring, and claw care is most important in the sense of avoiding focal stress in the bovine claws.

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