The Effect of Concrete Floor Roughness on Bovine Claws Using Finite Element Analysis

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ABSTRACT

The interaction between bovine claws and a concrete floor with defined roughness and friction coefficients is described using a finite element model. The model was built by using x-ray tomography scanner images of an unloaded fore and hind bovine claw. These images were used to reproduce the geometry of the claw horn capsule, which was used to create a finite element model. Young's moduli of 382, 261, and 13.6 MPa were attributed to the dorsal wall horn, abaxial and axial wall horn, and bulb horn, respectively. Poisson's ratio was set at 0.38. The horn was considered an isotropic elastic material. The model was completed by introducing a rigid support that simulated a concrete floor. The floor was moved to establish contact with the claw and was loaded with a force of 2 or 6 kN. The top border area of the horn capsule was fixed, but angular rotations were allowed. With this model, the effect of varying floor roughness and claw-floor friction on contact pressures and von Mises stresses in the claw horn could be evaluated. This was demonstrated by simulating the contact between the claw models and a smooth and rough floor with a center-line roughness value R_a of 0 or 0.175 mm, respectively, either without friction or with a static coefficient of friction of 0.75 and a dynamic coefficient of friction of 0.65. Contact pressures ranged from 2.14 to 27.55 MPa. The roughness of the floor was the main determinant in subsequent contact pressures. Maximum von Mises stresses were registered in the claw sole and were mostly between 5.04 and 16.44 MPa, but could be higher in specific situations. The variables claw (fore or hind) and floor (smooth or rough) had significant effects on the contact pressures; in addition, the floor resulted in significantly different von Mises stresses in the claw horn. The variable friction (frictionless or with friction) had a significant effect on the von Mises stresses. The load did not result in significantly

different contact pressures and von Mises stresses because of the large increase in contact area with the exerted load.

Key words: bovine claw, concrete floor, contact pressure, finite element modeling

INTRODUCTION

Because of the increasing intensity of modern farming, cows spend more time in cattle housing than ever, at the expense of walking at pasture. Despite the many advantages of concrete floors, animals often show claw diseases that are the direct and indirect effects of the roughness and slipperiness of the floor (McDaniel and Wilk, 1991; Frankena et al., 1992). Many claw diseases are caused by traumata of the dermis of the sole, which are sequelae of an extreme local overload (Distl and Mair, 1993). Monitoring of foot-to-ground pressure distributions may provide insight into the relation between high local pressures and foot lesions. Several researchers have recorded ground reaction forces and pressure distributions beneath bovine claws. Tous-saint-Raven et al. (1985) and Ossent et al. (1987) studied the distribution of the vertical ground reaction force over the medial and lateral claw. Sato et al. (1988) measured the 3-dimensional (3D) forces applied by cow feet during walking; Sato and Hasegawa (1993) measured the forces during standing and lying; and Albutt et al. (1990) determined the forces during walking, together with the horizontal foot movements. Distl and Mair (1993) first registered the pressure distribution under claws of living cattle by using a force sensor consisting of small individual plate capacitors. The foot-to-ground pressure distribution was described in more recent literature (van der Tol, 2004; van der Tol et al., 2004; Carvalho et al., 2005), in which bovine claws were tested on metal pressure plates. We succeeded in determining the effect of floor roughness on contact pressure distributions with a high resolution by introducing thin-film electronic sensors (Tekscan 5101, Tekscan Inc., South Boston, MA) between bovine claws from cadaver limbs and various concrete panels (De Belie

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and Rombaut, 2003; Franck and De Belie, 2006). In contrast to previous studies in which pressures between claws and the measuring plate were recorded, this technique allowed us to determine the pressures between claw specimens and concrete floors, and hence to investigate the effect of floor surface properties. These results could be used to examine the validity of the model presented in the current article.

Finite element analysis (**FEA**) is a modern engineering technique with great potential for stress evaluation in different materials under load. It has been used in veterinary research to model equine hooves (McClinchey et al., 2003; Thomason et al., 2005a,b) and bovine claws (Hinterhofer et al., 2005, 2006). The material properties of the bovine claw horn were determined previously (Franck et al., 2006). The average Young modulus and yield stress of the bovine claw horn were measured as a function of the horn location (dorsal, abaxial, bulb) and the test velocity (to confirm the visco-elastic behavior). In addition, the Poisson ratio was obtained.

Roughness and frictional properties of concrete floor surfaces are described in detail elsewhere (Franck et al., 2007). In that article, the static and dynamic coefficients of friction between fore and hind bovine claws and dry and wet floors were determined by using the "drag method" (a loaded bovine claw was dragged by using a hand-operated winch over a flat floor sample while the tensional force was recorded). Five concrete floor panels with different roughnesses were used. A geometrical model of a bovine claw was created based on x-ray images (Franck et al., 2005). This approach was continued. It is a straightforward method that easily allows the real thickness of the claw sole and wall to be taken into account. McClinchey et al. (2003) and Thomason et al. (2005b) generated a model parametrically (i.e., departing from measurements that describe the hoof shape): for each hoof, X/Y coordinates of points on the circumference of the bearing border and the proximal border were recorded, and a shell with the basic shape of a real hoof was generated. The horn capsule was then generated by adding a certain thickness to the contour image. The latter method has the advantage that the effect of changes in claw conformation can easily be investigated, which is not the case in our current model. Hinterhofer et al. (2005, 2006) digitized a dry lateral hind claw capsule with a 3D stereo scanner by using the visual light spectrum. In our model, the complete structure of both claw capsules was created.

In the current paper, finite element modeling (**FEM**) was used to study the contact zone between the bovine claw and concrete floor. The general aim of the contact simulations was to identify the areas on the surfaces that were in contact and to calculate the contact pres-

ures generated. The effect of surface roughness of the support on von Mises stresses and on contact pressures was assessed, allowing for a real comparison with experimental contact pressure studies.

MATERIALS AND METHODS

Bovine Claw Preparation

A fore and a hind limb of a freshly slaughtered 7-month-old calf were taken from the abattoir. The claws had healthy and normally shaped horn capsules and soles because they were taken from a young animal that was kept on wooden floors. The sole did not undergo any trimming or other preparation. The limbs had been cut off the just-slaughtered animal at the metacarpus-metatarsus and then cleaned and frozen until used.

Bovine Claw Model Creation

Computerized X-Ray Microtomography Image Generation. The computerized x-ray microtomography (μ -CT) scanner used was a Tomohawk system (AEA Technology, Warrington, UK). The system consisted of a HOMX-161 microfocus x-ray source (Philips, Hamburg, Germany) and an Adimec MX12P (Adimec Advanced Image Systems, Eindhoven, the Netherlands) charge-coupled device camera. The x-ray source remained stationary, but the claw turned around by means of stepping motors. The claw was rotated over 187°, and for each turn of 0.5°, an image was taken. All these images were then used as input for the reconstruction, which yielded approximately 450 slices (all in the XY plane) along the height of the claw (i.e., the Z axis).

The reconstruction was performed with dedicated Tomohawk software. The voxel (volume pixel) size as well as the distance between the slices was 0.217 mm for the fore claw and 0.215 mm for the hind claw. This value, which is the resolution, depended on the distance between the x-ray source and subject and the x-ray source and charge-coupled device camera plate (these distances were not exactly the same for the scans of the fore and hind claw; because the fore claw was slightly larger, the field of view, and hence the distance, had to be changed). The x-ray source was fed with a voltage of 120.5 kV and a current of 0.29 mA; the iris position (opening) was 94.3%. A filter consisting of 0.82-mm-thick Cu was applied in front of the x-ray source. This filter absorbed much radiation, a measure that was necessary to augment the contrast between the horn capsule and inner structures.

The claws were scanned in the unloaded frozen state, which added to their stability during the motion of the turntable. The frozen limbs were fixed in a polyvinyl

Figure 1. Claw in front of the x-ray source.

chloride tube to avoid the slightest movement during the scanning process, because this would have resulted in blurred images. Figure 1 illustrates this test setup.

μ -CT Image Processing. The scanned image slices were processed with the software package Mimics 9.11 (Materialise NV, Leuven, Belgium). Mimics 9.11 is a 3D image-processing and editing software that translates scanner data into full 3D images. Mimics 9.11 works through applying threshold masks with different gray values on the μ -CT slices (e.g., to retain only the horn structure). The slices were 512×512 pixels and were manually imported into Mimics 9.11. Each pixel was described with 2 bytes. The voxel size provided by the Tomohawk software after reconstruction was required to regenerate the scans in Mimics 9.11 with their real dimensions. While importing the slices into Mimics 9.11, only the slices that contained parts of the horn capsule were selected for use; other slices were discarded.

An example of a μ -CT slice is shown in Figure 2 (left). Figure 2 (right) shows the same slice, but the gray values above a certain threshold value were converted to white, whereas the lower gray values were converted to black. With Mimics 9.11, these operations were automated and the result could be checked in real time. In

Figure 2 (right) there is still “noise” (isolated white specks between the bone and claw wall), which cannot be removed purely by changing the threshold value. This noise occurs because of the low contrast between the tissue surrounding the bone and the claw wall horn. Mimics 9.11 offers tools for refurbishing the images; for example, masks with different thresholds can be subtracted from or added to each other and small cavities in the structures can be filled (Materialise NV, 2006). Most noise still had to be removed manually by editing each slice (deleting specks not belonging to the horn wall, filling cavities in the horn wall, and emphasizing the contours of the horn wall).

The result of the manipulations in Mimics 9.11 should be a smooth surface mesh with uniform triangles. The sole of the claw was the most important part because it was essential for calculating the pressures in the contact zone. The inner surface of the horn capsule was rough and irregular, but because the inner surface was not important for the claw model, it was made smoother by application of global smoothing operations. In addition, local smoothing operations at a large number of locations were necessary to eliminate the small imperfections at the surface of the horn wall and sole. Sharp edges had to be avoided because these would pose difficulties for the FEA software (so-called singularities). Care was taken that the edge length of the triangles was smaller than the thickness of the horn capsule. The end result of the workflow was 2 smooth horn capsules with small and uniformly shaped triangles (Figure 3). The fore and hind claw model consisted of 163,386 and 150,729 triangles, respectively. These models were converted with Mimics 9.11 to an input file that could be read or treated by an FEA software package.

3D Claw Model Generation. The FEA software package used was Abaqus 6.6-1 (Abaqus Inc., Providence, RI). All operations and manipulations were performed through the graphical user interface Abaqus/CAE (Complete Abaqus Environment). Abaqus CAE is an interactive, graphical environment for Abaqus. It allows models to be created by producing or importing the geometry of the structure to be analyzed and decomposing the geometry into meshable regions (Abaqus Inc., 2006).

The first step in Abaqus was to import the input file made by Mimics 9.11 and build tetrahedral elements (C3D4 elements) on the edges of the triangles at the surface of the claw model. The transformation of surface mesh to volumetric mesh was performed with a built-in Abaqus feature. New input files were then written, and these input files were again imported into Mimics 9.11. In Mimics 9.11, material properties were assigned to all tetrahedral elements, depending on what morpho-

Figure 2. Original microcomputer tomography image slice 255 of the fore calf claw (left) and the same, but converted, slice revealing the horn wall and bone structure (right). Color figures available online (<http://jds.fass.org/>)

logical mask the elements belonged to. The horn capsule of the fore claw with the different morphological zones is shown in Figure 4 (the hind claw is similar). These material properties (i.e., Young's modulus E) were determined by Franck et al. (2006). Young's modulus of the bovine claw horn at a physiological moisture content (30% on average) amounted to 382 ± 98 MPa for the dorsal wall horn, 261 ± 109 MPa for the abaxial wall horn, and 13.6 ± 1.7 MPa for the bulb horn in bending (dorsal, abaxial) and compression (bulb) tests at a test velocity of 1 mm/min. Later, in Abaqus, Poisson's ratio ν (0.38; Franck et al., 2006) and density of the horn (a value of $1,200 \text{ kg/m}^3$ was used) were added to the model. The material was considered an isotropic elastic mate-

rial, although in reality, claw horn (i.e., keratin) is an orthotropic viscoelastic material.

Claw-Floor Interaction Model

At this point, 2 claw models were created, but to model the interaction between claw and floor, a hard concrete floor had to be added to this model. The floor was implemented as a "rigid" body: it was so much stiffer than the rest of the model that its deformation could be considered negligible. The advantage of using rigid bodies over deformable bodies is that the motion of a rigid body was described completely by 6 degrees of freedom at a reference point; modeling a component

Figure 3. Top view (left) and bottom view (right) of the meshed fore claw model. The coordinate system is shown in the lower left corner of the picture, the 1-2 plane corresponds with the XY plane, and the 3 axis corresponds with the Z axis. Color figures available online (<http://jds.fass.org/>)

Figure 4. Top (left) and bottom (right) view of fore claw (dark gray: dorsal wall; lighter gray: sole and bulb; lightest gray: abaxial and axial wall). Note the perfectly flat top border area that was required for applying boundary conditions. Color figures available online (<http://jds.fass.org/>)

as a rigid body produces significant computational savings without affecting the overall results. Moreover, an analytical rigid part does not have to be meshed (Abaqus Inc., 2006).

Floor roughness and friction were included as parameters in the interaction model. Two basic claw-floor interaction models were created: a model with a hypothetical smooth concrete floor with a center-line roughness value R_a equal to 0 mm, and a model with a concrete floor with a serrated profile that simulated a rough floor. The rough floor was constructed as a saw-toothed wave with an R_a value equal to 0.175 mm. This value corresponds to a brushed or a slightly sandblasted surface finishing (Franck and De Belie, 2006; Franck et al., 2007). The grooves of the floor were parallel to the plane of symmetry of the claw.

For both types of floors, 2 kinds of contact behavior were defined: either frictionless (a hypothetical case) or with friction. In the case of friction between the claw and floor, the static coefficient of friction μ_{stat} was set at 0.75 and the dynamic coefficient of friction μ_{dyn} was set at 0.65. These friction values correspond to the friction between a bovine claw and a brushed, dry concrete surface as determined by Franck et al. (2007). Although the simulated loading conditions were quasi-static, the toes were allowed to move relative to the fixed top border area. This implies that contact nodes with the floor were allowed to move. Therefore, it was important to define a static coefficient of friction, which determines whether contact nodes will start moving, as well as a dynamic coefficient of friction, which was the relevant property once movement had started.

Two loads were applied: a load of 2 kN to approximate the weight of the cow on 1 limb when standing or walk-

ing, and a load of 6 kN to represent the complete weight of the cow exerted on 1 limb, which occurs when the animal is running or jumping. Van der Tol et al. (2004) measured vertical ground reaction forces of approximately 2 kN for squarely standing cattle. The load values of 2 and 6 kN were used previously (Franck and De Belie, 2006), which allowed comparison. Combination of the 4 tested traits resulted in 16 Abaqus input files.

The loading of the claw was performed in 2 steps: a “motion” step and a “point load” step. During the motion step, the floor approached the claw until contact was established. This operation was performed in a fast manner (0.0001 s) to keep the time elapsed before contact as short as possible with regard to total calculation time. The motion step enabled the floors to establish good and firm contact with the 2 toes of the claw. The motion step was implemented as gradually increasing (linear ramp function). During the point load step, a concentrated force pushed the floor further against the claw sole. Applying a point load to a rigid body had the same effect as applying a distributed load. The long time period (0.01 s, 100 times longer than the motion step) simulated quasi-static contact instead of pure dynamic contact. The point load step was implemented as a smooth step amplitude curve that automatically created a smooth loading amplitude. Use of this type of loading amplitude allowed us to perform a quasi-static analysis without generating waves caused by discontinuity in the rate of applied loading (Abaqus Inc., 2006). The quasi-static loading conditions were similar to those during the experiments performed on claws in a hydraulic compression machine (Franck and De Belie, 2006). The motion and point load steps were executed consecutively (total time = 0.0101 s). Each step con-

Figure 5. Assembly of the fore claw and rigid concrete surface as seen in the XY plane. The reference point and the coordinate systems (one global, one local for the claw, and one attached to the floor) are visible in the drawing. Color figures available online (<http://jds.fass.org/>)

sisted of 20 field frames (arbitrary moments during a step at which a snapshot of the situation was taken and data were saved). In the current study, the analysis was performed with Abaqus/Explicit because it was better suited for modeling brief, transient dynamic events, such as impact problems (Abaqus Inc., 2006). Furthermore, the general contact algorithm was used.

A reference point was assigned to the center of the floor. The motion (implemented as a boundary condition), the mass, and the point load were all applied to this reference point. In addition, a local rectangular coordinate system was assigned to the floor. Fixing of the top border area of the horn capsule was implemented as a boundary condition. All nodes in the XY plane (i.e., the plane of the top border area) were kept fixed in all 3 directions to restrain them from upward vertical motion, but angular rotations were allowed. The assembly of the fore claw on a smooth floor is illustrated in Figure 5.

Abaqus allows examination of both the contact pressures between claw and floor and the von Mises stresses in the claw horn. The contact pressure is the force exerted at the contact interface on an infinitely small surface area, divided by this area. The von Mises stress σ_{comp} within the material is a comparative stress value that allows evaluation of how the 3 orthogonal principal stresses, σ_1 , σ_2 , and σ_3 , have to be confined in a triaxial stress situation. It can be determined by the equation

$$\sigma_{\text{comp}} = \{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]/2\}^{1/2},$$

Table 1. Maximum contact pressures and von Mises stresses generated in the point load step (2 and 6 kN) of the fore claw models (n = 20 frames)

Floor type	Friction	Contact pressure, MPa		von Mises stress, MPa	
		Mean	SD	Mean	SD
Smooth	Friction	12.76	1.28	15.90	0.57
	Frictionless	12.21	1.77	14.42	1.31
Rough	Friction	19.54	1.89	16.44	1.68
	Frictionless	23.20	2.77	16.17	1.76

with σ_1 , σ_2 , and σ_3 being the 3 principal stresses.

Abaqus yielded results for a large number of traits, but only the contact pressures between claw and floor and the von Mises stresses in the claw were considered. For each of the 20 frames in each step, the maximum values of these measures were entered into a Microsoft Excel file (Microsoft Corporation, Redmond, WA) and further statistical analysis was done with SPSS 12.0 (SPSS Inc., Chicago, IL). The contact pressures were the most important traits, because they could be compared (within certain limits) with the mean and peak contact pressures determined by Franck and De Belie (2006).

RESULTS

The maximum contact pressure encountered in the motion step was 170.60 MPa with the hind claw (on a smooth floor with friction) and 100.00 MPa for the fore claw (on a rough floor with friction). The maximum von Mises stress encountered in the motion step was 21.57 MPa for the hind claw and 21.28 MPa for the fore claw. The high values were due to the impact of the floor onto the claw sole.

The maximum stresses obtained by the Abaqus analyses for the point load step are summarized in Tables 1 and 2. The maximum contact pressure encountered in the point load step was 27.55 MPa at the contact surface of the fore claw and 825.90 MPa at the contact surface of the hind claw. This last value is extremely high; values above 30 MPa occurred only in the case

Table 2. Maximum contact pressures and von Mises stresses generated in the point load step (2 and 6 kN) of the hind claw models (n = 20 frames)

Floor type	Friction	Contact pressure, MPa		von Mises stress, MPa	
		Mean	SD	Mean	SD
Smooth	Friction	3.85	1.44	5.04	0.74
	Frictionless	6.37	4.39	5.22	0.99
Rough	Friction	264.07	257.79	66.35	59.27
	Frictionless	121.82	217.79	15.10	9.33

Figure 6. Contact pressures between the fore claw and the rough floor with friction between the claw and floor; the grooves of the floor are parallel to the second axis. Color figures available online (<http://jds.fass.org/>)

Figure 7. Contact pressures between the fore claw and the rough floor with friction between the claw and floor. The floor was omitted from this image. Color figures available online (<http://jds.fass.org/>)

of the hind claw in combination with a rough floor, predominantly (i.e., not in all cases) when friction was involved (Table 2). In all other cases, contact pressures between 2.14 and 27.55 MPa were found. The maximum contact pressure found on a smooth floor was 21.81 MPa (hind claw).

The results (maximum values for each frame in each step) for both the motion and point load steps were analyzed by 1-way ANOVA, and some general conclusions could be drawn. The first important conclusion was that the load had no significant effect on the contact pressures and the von Mises stresses. There was no significant difference between the results for the loads at 2 and 6 kN. The variables “claw” (fore or hind) and “floor” (smooth or rough) resulted in significantly different ($P < 0.05$) contact pressures, but the variable “floor” also resulted in significantly different ($P < 0.05$) von Mises stresses. The variable “friction” (with friction or frictionless) resulted in significantly different ($P < .05$) von Mises stresses. This means that friction had no effect on the contact pressures and the claw had no effect on the von Mises stresses. When only the results of the point load step were kept, the global conclusions remained valid. The variable “frame” (i.e., the frame number) did not result in significantly different contact pressures and von Mises stresses. The combination of the effects of different parameters was determined with a univariate General Linear Model; claw, floor, and friction were considered fixed effects. In the case of contact pressures, the floor had 44% more effect than the claw and 8.3 times more effect than the friction, and in the case of the von Mises stresses, the floor had 6.5 times more effect than the claw and 1.9 times more effect than the friction.

Figures 6 and 7, respectively, with and without the floor, illustrate the contact pressures generated between the claw and the (rough) floor. Only at the nodes where contact was made were pressures registered. The contact images are similar to the images generated by Franck and De Belie (2006) with the Tekscan sensors, as illustrated in Figure 8. The maximum von Mises stresses encountered were 18.93 MPa in the fore claw and 131.40 MPa in the hind claw. This highest value again occurred in combination with a rough floor and with friction. These maximum stresses were found in the sole of the claw and not in the horn wall. The lowest value of all maxima noted for the von Mises stress was 3.82 MPa (hind claw on a smooth floor without friction). Claw wall stresses remained below 4 MPa.

DISCUSSION

Claw-Floor Interaction Model

Global and local smoothing operations on the claw model kept the original geometry and the area of the sole intact; only small imperfections were removed. In addition, some sharp edges (e.g., small creases at the sole) had to be removed prior to the FEA calculations. In this way, a quite realistic model of the claw was obtained. As a boundary condition, all nodes at the top border area were restrained from translational movement, but angular rotations were allowed. This boundary condition simulated the boundary conditions well during contact pressure measurements on cadaver claws in a test bench (Franck and De Belie, 2006). Here the claw was cut from a frozen limb just above the coronary band and was solidly assembled in an epoxy resin block. Still, both the experimental setup and FEM

Figure 8. Contact pressure distributions determined experimentally for 3 different cattle claws on a concrete floor with $R_a = 0.162$ mm under a load of 6 kN (the legend is in MPa). Color figures available online (<http://jds.fass.org/>)

lacked the dynamics of the claw in vivo, because movement of the 2 toes was restricted. In the model, the claws could not move relative to each other, as real claws do. This means that the model could not simulate load redistributions between toes. Hinterhofer et al. (2005, 2006) modeled only a lateral hind claw capsule and reported that this made it difficult to develop realistic loading patterns, because the stabilizing and load-carrying effect of the contralateral claw were missing.

In the current model, the bovine claw was treated as a hollow structure (i.e., a claw capsule) without internal pressure, as described in previous literature (Hinterhofer et al., 2005, 2006; Franck, 2006). The claw model was loaded via a point load on the floor. The load was transferred over the horn wall, and the peak stresses in the horn wall would decrease gradually with further distance from the sole. Buckling of the claw capsule did not take place. Filling the horn capsule with a viscous liquid or elastic material would have helped transfer the shear forces over the claw wall, but this would have made the model more complicated. In reality, the distal phalanx is connected to the horny capsule via the suspensory apparatus and its force-transmitting fibers (Simmons, 2004). Implementing the physiological method of loading would require the inner nodes of the dorsal and abaxial wall of the claw model to be loaded, because this would be a realistic simulation of how the distal phalanx transfers force onto the horn wall when loaded. The different loading conditions in the current study (via a point load on the floor) and in those of Hinterhofer et al. (2005, 2006; more realistically distributed over the inner nodes of the dorsal and abaxial wall) apparently did not result in large differences at the level of the von Mises stresses. Theoretically, one would expect differences mainly in the upper parts of the claw wall, where the internal loading is small for the Hinterhofer loading conditions (whereas it equals the full external load under our loading conditions). Nevertheless, when the weight-bearing surface is approached, the differ-

ences will become minimal. Because the results compared here were mainly the maximum von Mises stresses, which occur in the weight-bearing border and the bulb, this may explain the comparable results.

The orientation and the viscoelastic behavior of the claw horn were not taken into account in the FEM. These extra measures probably would have resulted in a different deformation of the claw capsule and in different von Mises stresses, but the contact pressures were presumed to be reliable.

McClinchey et al. (2003) studied the effects of equine hoof shape measurements on capsule stresses and strains, and Thomason et al. (2005a,b) compared strains and stresses in the hoof capsule obtained with FEA with strains recorded in vivo. They did not introduce a floor in their model, but restrained the nodes on the bearing surface of the wall from downward vertical motion. Thomason et al. (2005b) determined ground reaction forces, but not contact pressures. Hinterhofer et al. (2005, 2006) introduced a supporting surface in their model. Hinterhofer et al. (2005) defined 2 supports representing a soft surface (modulus of elasticity of 0.5 N/mm^2) and a hard surface (modulus of elasticity of $1,000 \text{ N/mm}^2$). Hinterhofer et al. (2006) investigated the difference between slatted and solid floors. In all cases, contact nodes were allowed to move according to a static coefficient of friction of 0.6. They calculated von Mises stresses in the claw capsule, but not contact pressures between the claw and the support.

A crucial part in this interaction model was the moment the contact between the claw and floor took place. Applying a point load without first establishing initial contact seemed to pose problems with the FEA software. It was necessary to first make contact and then to apply the point load. Therefore, 2 steps were necessary. Two methods were possible for modeling the contact: keeping the floor fixed at a certain point and letting the claw land on the floor, or keeping the claw fixed and having the floor move toward the claw. In principle,

these 2 methods should result in the same conclusions, but for ease of implementation, the second method was chosen. Another issue was the way the floor moved toward the claw, more specifically, the angle, velocity, and clearance between the claw and floor. The floor could not be positioned perfectly parallel to the sole of the claw, because the claw model could only be considered as a collection of nodes and elements instead of a defined geometrical surface (the claw model was an “orphan mesh” in Abaqus, which means that the image is a stand-alone image without an existing Abaqus master structure; the claw geometry was not created in Abaqus, but was imported from Mimics 9.11). This meant that the floor would make first contact with the claw at a certain point and not at 2 or, better still, 3 locations simultaneously.

The grooves of the rough floor were parallel to the symmetry plane of the claw; a different angle between the grooves and the symmetry plane would probably have resulted in different contact pressures and von Mises stresses. In reality, the surface peaks and valleys are distributed randomly over the surface area.

Interpretation of Results

Except for the extreme values above 100 MPa in the case of a hind claw touching a rough surface, the calculated contact pressures were in the same order of magnitude as those determined experimentally by Franck and De Belie (2006). The largest contact pressure determined experimentally was 111 MPa. On floors with R_a values of 0.162 and 0.213 mm, average peak contact pressures for 20 claws (mostly fore claws) were approximately 18 and 20 MPa, respectively. Still, there was a large variability, depending on the individual claw (Figure 8). The maximum peak contact pressure calculated in the FEM for the fore claw on a rough floor ($R_a = 0.175$ mm) with friction (frictional coefficients were chosen close to the experimental values for the considered floors) was 19.54 MPa, which fits the experimental values well. The application of the hind claw on the rough floor seemed to cause a zone with obviously higher nodal displacements, and hence extremely high contact pressures and von Mises stresses (Figure 9). The differences in values between the fore and hind claw can be explained by the way the floor was hitting the claw sole, the claw conformation, or their combination (i.e., the angle, the zone where initial contact was established, and a “peak” of the rough floor touching a “peak” in the claw sole). Friction did not seem to play an important role. The main determinant seemed to be the roughness of the floor, although friction and roughness are closely related. In comparison, a contact image with a smooth

Figure 9. von Mises stresses of the hind claw on the rough floor with frictionless contact, indicating a zone with extremely high stresses (the circle-shaped deformation in the right toe). The floor itself was omitted from this drawing. Color figures available online (<http://jds.fass.org/>)

floor is shown in Figure 10. All other settings were the same as in Figure 9.

There was no obvious explanation for the lack of a significant difference between the calculated pressures at 2 kN and at 6 kN. Experimental results of contact pressure measurements between bovine claws from cadaver limbs and various concrete panels (Franck and De Belie, 2006) also showed only small differences between mean and peak contact pressures measured under a load of 2 and 6 kN, respectively. The load tripled, whereas the mean contact pressure increased by 21% and the peak contact pressure by 44%. This can be partly explained by the large increase in contact area,

Figure 10. von Mises stresses of the hind claw on the smooth floor with frictionless contact. Color figures available online (<http://jds.fass.org/>)

which was twice as high under a load of 6 kN compared with a load of 2 kN.

The calculated maximum von Mises stresses were encountered in the sole of the claw. Von Mises stresses were limited to 4 MPa in the claw wall above the weight-bearing surface. This corresponds with the claw wall stresses measured with strain gauges (Franck and De Belie, 2006) showing maximum stress values of 2 MPa.

The maximum von Mises stresses found in this study (range between 5.04 and 16.44 MPa when omitting the extreme values) could be compared with the results of a model claw being loaded squarely on a solid floor (Hinterhofer et al., 2005, 2006). Hinterhofer et al. (2006) found dense and high von Mises stress values of 13.5 MPa, predominantly in the weight-bearing border of the dorsal wall and in the bulb area. Moderate stresses occurred in the proximal axial wall (5.8 MPa); comparably less stress (1.1 to 3.8 MPa) was evenly distributed along the weight-bearing border of the rest of the axial and abaxial wall. Hinterhofer et al. (2005) reported stress values of 7.43 MPa in the center of the axial wall. Stress values in the abaxial wall rose to 2.77 MPa. Distinct stress peaks of 13.50 MPa were seen in the distal rim of the claw wall (at the sole).

Hinterhofer et al. (2005) found von Mises stress peaks in the center of the proximal axial wall and in the outer edge of the weight-bearing surface. In the current study, stress peaks were found in the sole of the claw and at the bottom of the abaxial walls.

Hinterhofer et al. (2005) found von Mises stresses in the claw-floor contact zone of 9.11 MPa at a few contact points in the dorsolateral footprint and beneath the heels. This value was comparable with the maximum von Mises stresses found in the current study (values between 5.04 and 16.44 MPa). In addition, they found lower stresses when the claw was loaded on a soft surface (peak value = 4.82 MPa). In addition, very few contact points were encountered.

One advantage of finite element models such as Abaqus is that they allow examination of contact pressures between the claw and floor and von Mises stresses in the claw horn. The relation between those 2 has not been well studied for biomaterials. Contact pressures at the surface result in a 3D stress distribution below the surface. Normal stresses reach the highest value just below the contact point. They decrease rapidly further away from the contact surface, but because of the normal stresses, shear stresses occur and reach a maximum somewhat below the surface. For metals, plastic deformation will occur when these shear stresses reach a critical value. A good estimation for the critical value of the contact pressure may be the yield stress of the material (van Beek, 2001). The yield stress of the bovine claw horn was 14.3 ± 3.3 MPa for dorsal wall horn and

10.7 ± 4.5 MPa for abaxial wall horn (Franck et al., 2006), a value that was overrun by both measured and calculated contact pressures at several locations, indicating the possibility of claw horn damage.

Hinterhofer et al. (2006) and Thomason et al. (2005a,b) used Poisson ratios of 0.3; in the current study, 0.38 (Franck et al., 2006) was used. This was not expected to lead to large differences in results. Linear elastic behavior was assumed for the claw horn, although, in reality, horn is a viscoelastic material. In addition, isotropy was assumed, which is a simplification of reality. Other authors (Hinterhofer et al., 2005, 2006; Thomason et al., 2005a,b) made the same assumptions. Douglas et al. (1998) showed, for horse hoof capsules, <15% difference in the elastic modulus when testing along the tubules compared with testing along the intertubular material at a tangent to the wall's surface. Thomason et al. (2005b) considered that the assumption of isotropy would not substantively alter the mechanical behavior of the models. Hinterhofer et al. (2006) attributed a modulus of elasticity of 600 MPa to the claw wall at the dorsal margin, dropping to 200 MPa for the bulbar region and the sole. These values were higher than the ones introduced in our model, based on our own previous measurements (Franck et al., 2006). A continuous change in modulus from the dorsal to abaxial wall, as implemented by Hinterhofer et al. (2006), might be more realistic than a strict zonal distinction as in our model, whereas for the bulb elasticity, an overall difference may be expected with the wall horn.

Hinterhofer et al. (2006) used frictional properties comparable to a static coefficient of friction equal to 0.6, a value that was higher than the static coefficient of friction used in this study. No roughness values were taken into account.

General Issues

Only the geometries of the 2 claw capsules of 1 front and 1 hind limb were used. In principle, comparison of the FEA results should be made to bovine claw capsules only. However, even if the shape of the claw capsule were identical, factors such as cleanliness, moisture content, individual claw wall and sole thickness, BW, and surface properties would need to be dealt with separately. Factors such as individual claw properties, trimming status, and standing time, with the possibility of selective overloading, may lead to greater stresses in the claw capsule than calculated in this study. In a real-life situation, the simplicity of FEA results is tempered by the complexities of bovine housing (Hinterhofer et al., 2005), yet the findings were supported by the values found by Franck and De Belie (2006).

CONCLUSIONS

Creating a claw-floor interaction model required much preparatory work and refinement. The calculated values and the experimental results determined by Franck and De Belie (2006) were of the same order of magnitude. Although in FEA, idealization of loading and boundary conditions and of material properties was required, the model provided acceptable results. Friction did not have a significant effect on the contact pressures between the claw and floor; the roughness of the floor was the main determinant in the contact pressures that occurred. Considering the large differences from the fore and hind claw, it was clear that the results cannot easily be extrapolated to all claws because of the variation in claw geometry. The finite element model results were valid only for these claws and for a squarely standing animal because of the (quasi-)static loading conditions.

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