Sole and bar effects on finite element modelling analysis of horse hoof

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Summary

Reasons for performing study: Previously reported finite element (FE) simulations constructed models with different approaches to dealing with the components of sole and bars. This study allows a more specific investigation of the effects of sole and bars in order to help elucidate the functions of these hoof capsule components.

Objectives: The aims of this work were to construct the geometric form of a horse hoof in a computer aided design (CAD) system for FE testing in order to investigate sole and bar functions so that an approach to dealing with them could be decided for further FE simulations.

Methods: The geometric form of a representative hoof capsule was modelled parametrically so that a range of solid models could be generated automatically. Six different FE models were generated using a combination of the presence or absence of the sole and bars, and different degree concavity soles.

Results: The presence of the sole in a model was shown to decrease the von Mises strain, heel expansion and the magnitude of displacement dramatically on the surface of the hoof wall. The von Mises strain at the heel area did not show a significant decrease with the presence of the sole in the FE simulation compared with the area of dorsal hoof wall and quarters.

Conclusions: The degree of sole concavity did not play an important role in either the distribution of von Mises strain or the displacement but omitting the sole in the FE simulations could give rise to an overestimation of von Mises strain and deformation. Omitting the bars could result in a loss of accuracy of von Mises strain data in the heel area. Therefore, the inclusion of the bars, together with a flat sole were decided upon for further hoof construction for further FE investigations.

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Introduction

The FE modelling technique, which provides a sophisticated method of simulating the theoretical response of an object under loading based on material and structural properties, has great potential for investigating biomechanical function (Newlyn et al. (1998); Reilly (2001) and Collins, (2004)). FE simulations have been used to investigate the effect of flat horseshoes, raised heels and lowered heels on hoof biomechanics (Hinterhofer, et, al., 2000); and to predict effects of farriery on the equine hoof (Hinterhofer, et al., 2001); to analyse the strain and stress in the equine hoof capsule (Thomason et al., 2002) and to isolate the effects of hoof shape measurements (McClenchey et al., 2003).

The finite element (FE) method provides a mathematical solution to analyses of complex systems by sub-dividing the system into the individual components or ‘elements’, whose behaviour is readily understood. It then rebuilds the original system from such components to study its behaviour, (Zienkiewicz and Taylor, 2000). The accurate representation of the ‘system’ is a key factor in accurate prediction by FE simulations.

The previously reported FE models have followed a similar construction methodology to Newlyn et al. (1998) for the FE investigation of the donkey foot. However, there are still differences between models from different groups in the construction of the ‘system’ of the horse hoof capsule. The model of Hinterhofer et al. (2000, 2001) contained bars which were lacking in the model of Thomason et al. (2002), and McClenchey et al. (2003). The sole was constructed to be concave in all previous models, while the degree of concavity was not indicated. This can lead to confusion in the FE modelling of equine feet and so the question remains: what are the biomechanical effects of bar and sole structures, and how much can we simplify them in modelling systems without losing their effects?

The insensitive sole and bar cover and protect the sensitive structures inside the hoof capsule, but the importance of them has not been investigated (Balch et al., 1995) and they have not been given enough detailed concern yet in FE investigations. Nevertheless, a thick sole was believed to reduce hoof expansion during weight bearing by Stashak et al., (2002) and excessively prominent bars may induce lameness associated with undue hoof rigidity according to Balch et al. (1991).

The aims of this paper were to construct the geometric form of a horse hoof in a computer aided design (CAD) system for FE testing and to investigate the sole and bar functions by FE simulation so that an approach to dealing with them could be decided for further FE simulations. The geometric form of the hoof capsule was modelled parametrically so that a range of solid models could be generated automatically. Three soles with different degrees of concavity were modelled. Six models with different combinations of sole and bars were modelled to investigate deformation and von Mises strain in the hoof wall by FE simulations in order to gain a further understanding of hoof function. The different model combinations are listed in Table 1.
Materials and Methods

1) Representative CAD model of hoof wall

A representative CAD model of the hoof wall was generated parametrically to characterize the hoof shape using Unigraphics NX4. The methodology of constructing the CAD model was adapted and extended from the donkey hoof characterization technique of Newlyn et al. (1998). The parameters were selected to characterize the geometric form of the hoof wall and were modelled by variable values rather than fixed values, so that the new model could be generated by importing new parameter values without having to repeat model construction.

The solear surface was constructed using seven measurement sites as shown in Fig 1 orthogonal with the central axis in the xy plane: 25% percentage of the capsule depth (P_1); 40% percentage of the capsule depth (P_2); the widest hoof width position (P_WHW), 60% percentage of the capsule depth (P_3); 75% percentage of the capsule depth (P_4); and the measurement site for P_5 characterized the position of the bar apex and the capsule depth (CD). The outside outline was constructed by the linear distance from the bearing border (BB) to the central axis on each measurement site. The inside outline was then defined by the thickness of the wall at each measurement site.

After the solear outlines were defined, the dorsal hoof wall angle (DHWA), dorsal hoof wall length (DHWL) were constructed on the yz plane by a straight line with the angle of DHWA with the xy plane and the length of DHWL. Similarly, the heel angles (HA) and heel length (HL) were constructed from the measurement site of CD by two straight lines. They were then inclined in the medio-lateral direction to achieve the lateral heel angle (LHA) and medial heel angle (MHA). Thus, the plane of the coronary band (CB) was defined by these three lines.

The lateral hoof wall angle (LHWA), and medial hoof wall angle (MHWA) were constructed in the xz plane of the measurement site of p_WHW position to achieve the inclinations in the medio-lateral direction. Similarly, for the measurement site of P_1, P_2, P_3, P_4 and P_5 the inclinations in the medio-lateral direction were constructed in the xz plane on each measurement site.

2) Sole and bars construction

Three different solear possibilities were constructed from the inner surface of the hoof wall. The centre of the sole was notched where the frog would be. All soles had a constant thickness of 10 mm. The concavity was modelled by lifting the centre of the sole from the ground while the rim remained in the original position. This gave a ‘degree of concavity’ parameter at the centre of sole, measured in mm. The ‘degree of solear concavity’ modelled were: (a) 0mm (flat); (b) 2mm (slightly concave) and (c) 10mm (concave) (Fig 2).
Two bars were constructed from the two most caudal points on the outside outline of the BB along the notches of the sole and defined by the parameters of length (in the xy plane) and height.

3) Model construction and mesh generation

The values for key parameters of the representative model in this study were adopted from the average values of the control group of horse hooves in Kane et al., (1998) as listed in Table 2. However, this CAD model used a total of 62 independent parameters for the complete definition of the geometric form including the 10 given by Kane et al. (1998). Once the required values of parameters were imported into the template model, all components were meshed by 3D tetrahedral elements finite elements mesh, with a size of 5mm in Unigraphics NX4 with an MD Nastran solver. Post processing finite elements results were expressed as von Mises strain and the magnitude of displacements. These were chosen in order to give data for comparison with other authors, such as Xu et al., (2007). In addition, von Mises strain values in models can be more easily experimentally validated in further work as demonstrated by Godara and Rabbe (2007).

4) Material properties

The Poisson’s ratios were assigned to be 0.3 for all the components, which was also followed by Hinterhofer et al. (2000), Hinterhofer et al. (2001), Thomason et al. (2002) and McClinchey et al. (2003).

The stratum medium (SM) was divided into 3 layers. The elastic moduli of the outer layer and inner layer of the SM, and of the sole which were used are listed in Table 3 and were taken from the literature. The elastic moduli of the middle layer of the SM was estimated as an average of the outer layer and inner layer. All the components were assumed to be linear elastic material.

5) Boundary conditions for all models

Boundary conditions for all models consisted of loading conditions and constrains at the boundary of the model.

Loading conditions

A vertical loading of 5000N were applied on the inside surface of the capsule according to the mesh geometry, so that the load was evenly distributed over the internal hoof wall area with a constant vertical force. The distribution of load was simulated in the same manner as that used by Newlyn et al., (1998).
**Constrains at the boundary**

The solear surface is constrained in the Z direction. The bearing border (BB) of the mid-line dead centre (MDC) (after Reilly et al., 1996) was fixed in all directions in the same way as Newlyn et al., (1998). There were no constraints applied to the proximal part of the capsule at the coronary band (CB). No friction was assigned between the solear surface and the ground so that the size and shape of the deformations would not be affected by the ground.

6) **Positions being investigated**

The von Mises strain and displacement at 15 positions distributed across the area of the dorsal hoof wall (DHW), quarters and heels of the hoof wall surface were investigated under the above boundary conditions as shown in Fig. 3.

**Results**

Displacement results are shown in Fig 4. The magnitude of the displacements in the two groups without sole showed a different pattern around the hoof wall compared with those groups with sole. The average magnitude of the displacements in different area of the capsule are shown in Fig.5. In the two groups without sole, the average displacements at the heel area was more than 5 times that of the DHW area. The differences decreased in the groups with sole, which was 1.7-2.2 times in the four groups (shown in Table 4). This indicated that the deformation was reduced greatly by the sole. With increasing concavity of sole, the difference between the displacements at the DHW area and the heel area were decreased further, but the effect was slight (shown in Fig. 5). The average displacements in ‘with bar’ groups were smaller than the ‘without bar’ groups, but also the effect was slight.

The average displacements of the quarters and heels area in the x direction, which was the direction of heel expansion, are shown in Fig.6. The heel expansion of the ‘with sole’ groups was reduced greatly compared with the ‘no sole’ groups. This reduction was of more engineering significance in the quarters than in the heels. The heel expansion of the ‘with bar’ groups showed a slight decrease compared with the ‘without bar’ groups.

The von Mises strain at different positions is shown in Fig. 7. The von Mises strain in the two ‘without sole’ groups were close to each other in most positions. The von Mises strain in the four ‘with sole’ groups were decreased in all the positions.

The average von Mises strain in different areas is shown in Fig. 8. The von Mises strain decreased significantly in all with sole groups compared with those ‘without sole’ groups. In particular, the von Mises strain at the heel area, surprisingly, did not show a significant decrease with the presence of the sole in the FE simulation. The average reductions of von Mises strain by the presence of the sole were only 29.8% at the heel area, while the average reduction at the DHW and
quarter area were 68.4% and 72.4% respectively. With increasing sole concavity, the von Mises strain decreased slightly in all DHW, quarter and heel areas but the effects were slight. In all the simulations, high von Mises strain concentrations occurred at the junction of the hoof wall and sole in all ‘with sole’ groups (only the group of ‘flat sole with bar group’ is shown in Fig. 9).

The average von Mises strain at the heel area showed a decrease in the ‘with bar’ groups compared with the ‘without bar’ groups (shown in Fig.8).

Discussion

Reilly et al. (1996, 1998) have shown that the SM of the hoof wall can be considered as a four layer system using tubule density counts. When tubule morphology is used as a defining method, then the SM appears to have three layers according to Konig (2001) and Patan (2001). A three layer approach was used in this model. However, future work should compare results with a four layer SM in order to review any subtleties of functional significance related to this anatomy.

The sole is a concave structure from side to side and also from front to rear between the frog and the bearing border of the wall. It is separated from the hoof wall by the white line. This insensitive structure is considered by the farrier to act primarily as a protective covering for the sensitive tissue inside the hoof capsule rather than to have a function in weight bearing. Hence, use of it to bear weight was believed to initiate bruising by Balch et al., (1995). However, the decrease of both von Mises strain and displacement in the FE simulations that included sole in this study might indicate that the sole may also have a functional role in limiting the hoof capsule’s response to loading.

The FE investigation also showed that sole had significant effects in decreasing deformation. Both heel expansion and total deformation were decreased greatly by the sole. However, the decreasing of displacement in the heel area was smaller compared to that at the quarters and DHW. A similar effect occurred with von Mises strain. The von Mises strain remained high in the heel area even with the presence of the sole. These results could reflect a compromise of the sole to the heels: restrict the excessive deformation but allow heel expansion on some extent. This high strain at the heels which has been identified is worthy of further work in relation to heel problems in horses.

The FE investigation indicated that the more the degree of concavity of the sole, the more the decrease of von Mises strain and the magnitude of displacement, but the decrease was not significant for both von Mises strain and displacement. Without radiographic evidence, the degree of concavity of the sole is not easily obtained.

The presence of the sole gave a decrease for both von Mises strain and displacement, but the concavity did not play an important role in the decrease for both von Mises strain and displacement, a flat sole was decided to be included in the further investigations.
The FE simulations indicated a high level of strain during loading at the junction of the wall and the sole (Fig.9), which was known as the area of white line. During loading, this junction area should allow the wall and the sole deformed in different directions. It is believed that the white line allows independent movement of wall and sole during loading and thus prevents catastrophic failure of the hoof capsule (Reilly 1997). This could be a functional reason for high strain concentrations in this area. However, the high strain in this junction area may increase the risk of failure compared with other parts of the hoof capsule and sole, and might also play a role in the pathomechanics of white line disease. This is an area for further study.

The functions of the insensitive bars are poorly understood. Balch et al. (1995) stated that bars may act as internal struts to inhibit heel contraction in the absence of normal frog pressure. But the bar is a sharply angled extension of the hoof wall, and the assumption was that it would act to prevent heel expansion. The FE investigation however showed that the decrease in displacement of heels in the direction of heel expansion was not significant. However, the presence of bars did decrease the von Mises strain in the heel area. From Fig. 8 it is concluded that omitting the bars in FE modelling work would lead to a loss of accuracy of prediction of von Mises strain in the heel, and thus, for future investigation it was decided to include the bars in the model.

Conclusions

The presence of the sole decreased the von Mises strain, heel expansion and displacement dramatically on the surface of the hoof wall. The von Mises strain remained high in the region of heel even when the sole was included in the model, despite the fact that the strain in other regions decreased by the presence of the sole. The degree of concavity did not play an important role for both the distribution of von Mises strain and displacement, but omitting the sole in the FE simulations could cause an overestimation of modelled von Mises strain and displacement. The bars affected the von Mises strain of the heel area, but did not strongly affect deformation. Omitting the bars in FE simulations could result in loss of the accuracy of von Mises strain in the heel area. Given that the absence of the sole could cause an overestimation of the strain and displacement but the concavity did not play an important role, and exclusion of the bars was likely to result in loss accuracy in the strain of the models, it was decided to include a flat sole and the bars in all model systems for further FE investigations.

Manufacturer’s address

1Unigraphics Solutions Inc. 13736 Riverport Drive Maryland Heights, MO 63043 USA

2MSC Software Corporation. 2 MacArthur Place, Santa Ana, CA 92707 USA
References


Words count: 3858 (including references)
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Fig 1. Measurements constructed in the representative CAD model
DHWA = dorsal hoof wall angle; DHWL = dorsal hoof wall length;
HA = heel angle; HL = heel length; CD = capsule depth;
LHWA = lateral hoof wall angle; MHWA = medial hoof wall angle;
HW = heel width; WHW = widest hoof width;

Fig 2 The three different soles

(a) Flat sole

(b) Slightly concave sole

(a) Concave sole
Fig 3 The 15 positions distributed on the hoof wall surfaces
CB= coronary band; BB= bearing border; DHW=dorsal hoof wall;
HWH=hoof wall height; MQ=medial quarter; MH=medial heel;
LQ=lateral quarter; LH=lateral heel, MDC=mid-line dead centre

Fig 4 The magnitude of displacement results of different sole and bar group

Fig 5 Average magnitude of displacements of different sole and bar group in different area
Average displacements on the x direction in area of DHW, quarter and heel

Different sole and bar combination

Fig. 6 Average displacements on heel and quarter area on the x direction of different sole and bar group

Comparison of von Mises strain

Without sole group
With sole group

Fig. 7 The von Mises strain results of different sole and bar group

Average von Mises strain in area of DHW, quarter and heel

Fig. 8 Average von Mises strain of different sole and bar group in different area
Fig. 9 The von Mises strain distribution of the ‘flat sole with bar’ group
<table>
<thead>
<tr>
<th>Components</th>
<th>no sole</th>
<th>no sole with Bar</th>
<th>flat sole no bar</th>
<th>flat sole with bar</th>
<th>slightly concave sole with bar</th>
<th>concave sole with bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Sole</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Concavity of sole</td>
<td>N/A</td>
<td>N/A</td>
<td>flat</td>
<td>flat</td>
<td>Slightly concave</td>
<td>concave</td>
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Table 1. The six model combinations

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWA (º)</td>
<td>72.8</td>
</tr>
<tr>
<td>MWA (º)</td>
<td>77</td>
</tr>
<tr>
<td>CD (mm)</td>
<td>119.4</td>
</tr>
<tr>
<td>P. WHW (mm)</td>
<td>43.6</td>
</tr>
<tr>
<td>DHWA (º)</td>
<td>50</td>
</tr>
<tr>
<td>DHWL, (mm)</td>
<td>88.9</td>
</tr>
<tr>
<td>HL (mm)</td>
<td>33.9</td>
</tr>
<tr>
<td>HA (º)</td>
<td>41.6</td>
</tr>
<tr>
<td>HW (mm)</td>
<td>65.4</td>
</tr>
<tr>
<td>WHW (mm)</td>
<td>124.5</td>
</tr>
</tbody>
</table>

Table 2. Value of key parameters in the representative model (after Kane et al., 1998)

<table>
<thead>
<tr>
<th>Outer layer of SM</th>
<th>1004 Mpa</th>
<th>Douglas et al., 1996</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle layer of SM</td>
<td>763.5 Mpa</td>
<td>Calculated the average from the outer layer and inner layer of hoof wall</td>
</tr>
<tr>
<td>Inner layer of SM</td>
<td>523 Mpa</td>
<td>Douglas et al., 1996</td>
</tr>
<tr>
<td>Sole</td>
<td>230 Mpa</td>
<td>Douglas et al., 1996</td>
</tr>
</tbody>
</table>

Table 3. The elastic moduli of dorsal hoof wall

<table>
<thead>
<tr>
<th>Average magnitude of displacement</th>
<th>no sole</th>
<th>no sole with Bar</th>
<th>flat sole no bar</th>
<th>flat sole with bar</th>
<th>slightly concave sole with bar</th>
<th>concave sole with bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHW(mm)</td>
<td>1.840</td>
<td>1.828</td>
<td>0.469</td>
<td>0.466</td>
<td>0.465</td>
<td>0.445</td>
</tr>
<tr>
<td>Quarter (mm)</td>
<td>3.518</td>
<td>3.514</td>
<td>0.619</td>
<td>0.569</td>
<td>0.569</td>
<td>0.514</td>
</tr>
<tr>
<td>Heel (mm)</td>
<td>10.700</td>
<td>10.353</td>
<td>0.987</td>
<td>0.894</td>
<td>0.864</td>
<td>0.736</td>
</tr>
<tr>
<td>Heel/DHW ratio</td>
<td>5.816</td>
<td>5.665</td>
<td>2.104</td>
<td>1.919</td>
<td>1.856</td>
<td>1.656</td>
</tr>
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Table 4 The average magnitude of displacement at different positions in different bar and sole groups