Numerical Simulation and Experimental Scheme for Monitoring Hoof Wall Structure and Health in Sport Horses

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Abstract: This study provides a computational model developed to demonstrate the possibility of monitoring hoof structure and health in equestrian sport. This is achieved by employing finite element simulation of three-dimensional heat flow from a surface heat source into a hoof structure while simultaneously sensing the surface temperature. The time evolution of the recorded surface temperature, transient curve, is used to investigate hoof structure and predict its intactness by comparing these curves for three different models. We have observed differences between the transient curves obtained from a normal hoof structure, a hoof structure containing a foreign material and hoof capsule subjected to wall separation. An experimental method for probing hoof profile was briefly discussed. It uses temperature sensor/heat source. The method can determine the thermal conductivity of the hoof along the hoof structure from the recorded transient curve. Thus, it displays the hoof structure by utilizing the thermal conductivity variation between the hoof parts.

1 INTRODUCTION

In all equestrian sports, the well-being of the horse is fundamental. Frequently the horse struggles with hoof problems. Often it is hard to detect the underlying damages hidden in the internal of the hoof. The hoof is composed of an external hoof capsule connected with the internal pedal bone by horny and fleshy plates (Nassau, 2004). Hoof capsule damages of different degrees are common in most horses. Injuries such as wall separation, submural infections and crack are caused by various factors including environmental conditions and specific athletic endeavours (Moyer, 2003), particularly the latter could disproportionally affect athletic horses. Here we discuss a computational method to monitor the status of a hoof by determining the presence or absence of foreign object in the structure. This is realized using thermal waves. The use of thermal wave for health care inspection can be achieved in several ways: the first one is thermography. It is a direct imaging of heat pattern on the surface of objects or scene (Ibarra-Castanedo, 2013). A second method requires the recording of the surface temperature to deduce the thermal transport property of the material, commonly referred as an inverse problem. The method proposed in this study belongs to the latter group. It works by supplying constant heat on the surface of the object and recording the change in temperature on the heat source and then predicting the property of the sample from the recording.

In this work, COMSOL Multiphysics software is employed to determine the numerical solution of the temperature distribution of a hoof due to external heat source and the change in temperature on the heat source due to its contact with the hoof. The model consists of concentric heat source placed on the hoof wall structure and provides constant heat for few minutes. The change in temperature on the heat source and the temperature distribution of the hoof is then retrieved. The above information can be used to determine the presence or absence injury (foreign materials or change in structural properties) in the hoof.

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An experimental approach to investigate the structural profile of the hoof wall is also included. The general experimental technique implemented is referred as hot disk method (Gustafsson, 1991). The method measures the thermal transport property of materials by only recording the change in temperature on the sensor. A recent extension of this method enables it to thermally profile a material along its depth. This approximation scheme and some examples are included in the reference (Sizov, 2016). Further detail examples and description on the experimental limitation and capabilities of structural profiling of materials along their structure is shown in (Mihiretie, 2016).

This contributes in understanding of hoof wall defects and could potentially help horses to have longer athletic careers and life.

2 MODEL

Three different models were designed to represent the situations in a healthy hoof and damaged hooves.

I. Normal hoof structure, fig.1.
II. Hoof structure with a foreign material inside the hoof capsule, fig.2.
III. Hoof capsule subjected to separation of wall.

Model I, represents a healthy hoof structure. It consists of three parts: hoof wall; bone and heat source. The external keratin material (hoof wall), surrounds the internal bone structure and the double spiral heat source (nickel wire) is placed on the outside surface of hoof capsule. In model II, a spherical foreign material is included in addition to the parts listed in model I. The foreign material assume the role of an infected part that developed some sort of fluid (pus) inside the hoof capsule. Thermal wave from the heat source travels through the hoof wall before it spreads to the bone structure. In model III, since the inside part of the hoof wall is exposed to air to represent wall separation, the heat wave is exposed to convective cooling from the inside part of the hoof capsule.

The models are generated using COMSOL Multiphysics V.5.2, the software uses the finite element method to describe the complex problem with a linear system of equations. This is achieved by dividing the geometry of the problem at hand into several subdivisions (elements), called meshing. Then the relevant quantity is approximated at each node of the element. Finally the solution for each element can be collected to form global solution for the entire geometry (Tabatabaian, 2014). The validation of COMSOL's heat transfer modules is documented in different studies (Gerlich, 2013, Suarez, 2014).

The aim of the simulation is to demonstrate the utility of the finite element analysis in the investigation of monitoring the structural integrity of hooves. This is realized by studying the thermal response of the hoof structure.

The governing equation that describes transient heat transfer in solids can be expressed as follows:

$$\rho c \cdot \frac{\partial T(r,t)}{\partial t} = \nabla \cdot (K \cdot \nabla T(r,t) + Q) \tag{1}$$

Where ρc is the volumetric specific heat of the material, T is temperature, t is the test time, K is thermal conductivity, r is position vector and Q is the heat source per unit volume.

It is difficult to solve eqn. 1 analytically for the present geometry, thus a mathematical tool for numerical solving of such partial differential equations is employed, using COMSOL.

COMSOL consists of different modules, thus a typical simulation starts by choosing the physics and study type. In this study, heat transfer module with time dependent study is used. Simulation time vector was introduced for the transient measurement, in the closed interval [0,320s], with increments of 0.1s during which a constant power of 0. 5 W is used. For solving, default solver is used.

Defining the geometry and type of materials follows naturally. Here they are defined to represent the different hoof status expressed in the model I-III. Finally, applying appropriate meshing, boundary and initial conditions comes to effect. The initial temperature considered for the entire system was set to be at room temperature (293.15K), and the following boundary conditions are considered:

- Extremities of the model are insulated.

$$\mathbf{n} \, . \, \mathbf{q} = 0 \tag{2}$$

Where $\mathbf{n}$ is normal vector and $\mathbf{q}$ is the heat flux by conduction.

- Thermal contact boundary condition is set between the heat source and the hoof wall and also between the hoof capsule and the bone.

$$-\mathbf{n}_{\boldsymbol{d}} \cdot \mathbf{q}_{d} = -h(T_u - T_d) + \boldsymbol{r}\boldsymbol{Q}_{\boldsymbol{b}} \tag{3a}$$

$$-\mathbf{n}_{\boldsymbol{u}} \cdot \mathbf{q}_{u} = -h(T_d - T_u) + (1 + \boldsymbol{r})\boldsymbol{Q}_{\boldsymbol{b}} \tag{3b}$$

Where h is the conductance; u (up) and d (down) subscripts refers to the two sides of the contact.

- The heat source is defined using thin concentric elements with over all heat transfer rate.
- Heat loss due to convection is considered in the case of wall separation.

  $$q_o = -h(T_{ext} - T) \qquad (4)$$

  Where q_o is convective heat flux and T_{ext} is external temperature.
- Physics controlled finer mesh element size is adapted for all the domains.

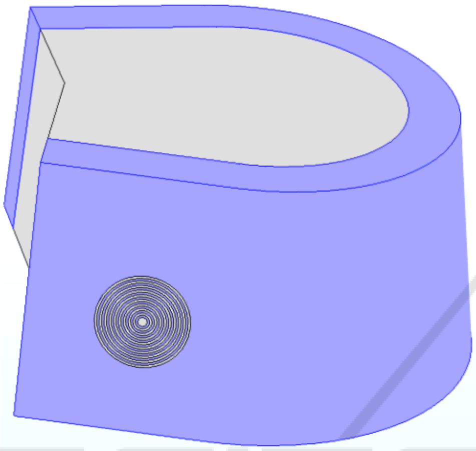

Figure 1: Model of hoof structure. The external blue structure is hoof capsule (keratin). The internal sliver part is the bone. The heat source represented by the concentric circles is placed on the side of the hoof wall.

The second model shown in fig. 2 consist of spherical object in the hoof capsule filled with fluid. It represents a possible pus caused by infection. In the simulation the thermal properties of such fluid is assumed to be similar to that of water.

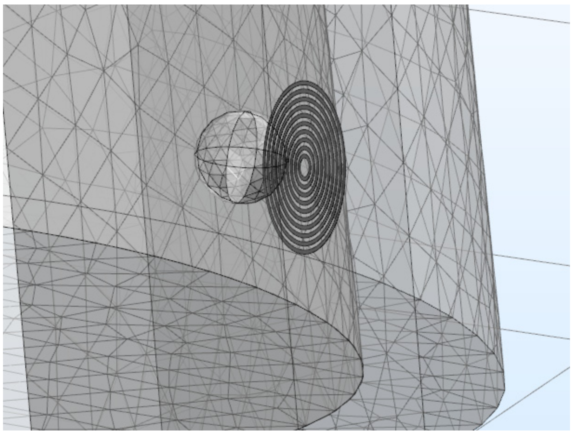

Figure 2: Meshed geometry showing the concentric heat source placed on the hoof surface and spherical foreign object inside the hoof capsule. Normal size meshing of COMSOL is used.

Table 1: Characteristic of materials used in the simulation.

Material	Thermal Conductivity W/(m.K)	Heat capacity J/(kg.K)	Density (kg/m^3)
Keratin	0.45	2000	1200
Bone	0.32	1313	1908
Nickel	90.7	445	8900
Fluid	0.6	4187	1000
Air	0.03	1005	1.2

The properties of keratin and bone were determined in a separate experiment (Gustavsson, 1994) whereas, the properties of the rest materials were imported from COMSOL material list.

3 RESULT AND DISCUSSION

As explained in sec. 2, heat transfer mode and transient analysis in conduction of heat in solids have been chosen. The temperature distribution of the hoof after constant heat supply from source for 320 seconds on a hoof with fluid is shown in fig.3.

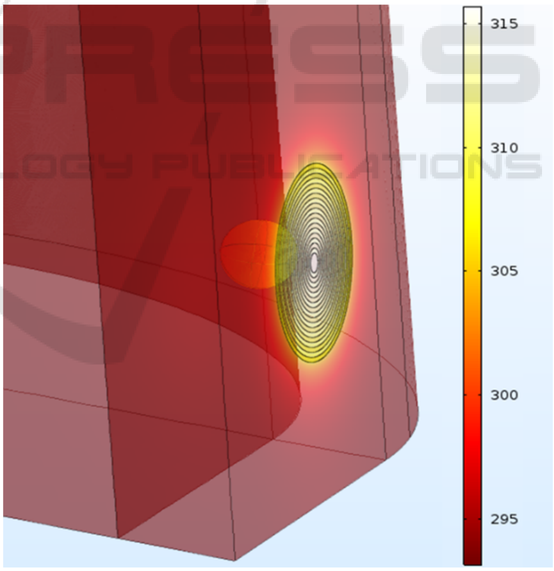

Figure 3: Temperature distribution of the hoof (K), at t =320 sec., with spherical foreign material in the hoof capsule, model II. Initial temperature of the hoof was 293.15 K.

The highest temperature (315 K, fig.3) which is at the heat source drops to room temperature as one goes away from the source.

The heat supplied from the source propagates into the hoof and cause change in temperature along the way. The way heat leaves the source depends on the thermal property of the hoof composition. Thus, computing the time evolution of the heat source, transient curve, one can predict the composition of the hoof profile. Fig. 4 shows transient curve of the heat source. The three curves represent the three different models discussed in sec. 2. The top dotted line is obtained from hoof subjected to separation of wall (Model III) whereas the middle solid line is the transient curve for heat source placed on the healthy hoof (model I) and the dashed line (Model II) is retrieved from a hoof with a foreign material inside. The curves represent the average change in temperature on the heat source volume in time.

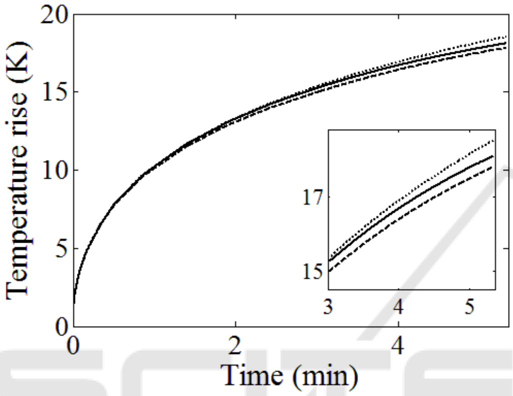

Figure 4: Temperature rise as a function of time. Each transient curve represents different models. Solid, dashed and dotted lines represent model I, model II and model III respectively. Inset: includes only measurements after 3 minute.

The presence of air (model III) instead of bone inhibits propagation of heat, as air is less thermal conductor, resulting higher temperature rise on the heat source compared to the case of a normal hoof composition (model I). However, in the case of model II, the fluid is more thermal conducting than hoof which enhance heat conduction resulting lower temperature on the source. The clear distinction between the three curves in fig. 4 occurred due to the presence of different composition in the hoof structure. Thus, comparing the transient curve of a particular hoof with the one obtained from a healthy hoof, it is possible to predict the intactness of a given hoof.

4 EXPERIMENTAL WORK

The experiment part of this study consist of thermal profiling using a transient plane source technique called hot disk method (Gustafsson, 1991). It is an ISO standard technique for testing thermal transport properties of materials (ISO22007, 2008). The technique works by using a sensor that can supply constant heat source to the hoof and simultaneously record the change in temperature. The thermal conductivity of the material is calculated from the recorded temperature. The hot disk thermal constants analyser can detect temperature differences with an accuracy better than 0.1 mK by utilising highly sensitive components (ISO22007, 2008). The sensor is made from double spiral nickel wire covered with thin polymer, kapton, fig. 5.

A special application of hot disk technique enables to approximate the thermal conductivity of the material along the heat wave penetration depth (Mihiretie, 2016), fig. 6.

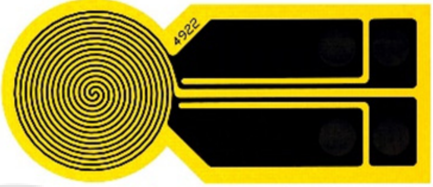

Figure 5: A hot disk sensor. Spiral wire nickel covered with polymer kapton.

Applying this technique to horse hoof requires to place the sensor on the hoof surface and record the change in temperature on the sensor as current pass through the sensor. Such experimental profiling was performed on conserved dead horse hoof. To keep the hoofs preserved all the measurements were performed in a fridge with a temperature of around 7 degrees Celsius.

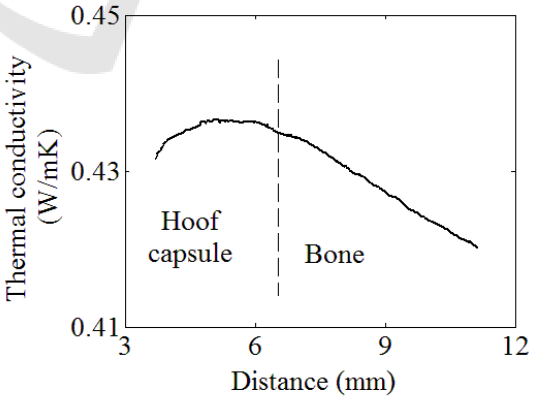

Figure 6: Thermal conductivity profile of conserved hoof. This hoof capsule is about 7 mm thick. Repetitive measurements are reproducible.

The experimental work was realized on a healthy conserved horse hoof. It reveals the hoof profile. The thermal conductivity plot demonstrate that the hoof capsule has higher thermal conductivity than the bone. The thermal conductivity starts to decrease as the heat wave reaches the bone structure. This gradual drop instead of sharp change at the interface is due to the fact that the calculation method uses an averaging technique. It is also worth to note that information about the part near the outer wall is missing due to interference from thermal contact resistance.

Experimental and modelling parameters were designed to be equivalent to each other, for instance the double spiral nickel wires were represented by concentric circles in the simulation. However, direct comparison between experiment and simulation is left for future work. This requires the simulation to be expressed in terms of thermal conductivity instead of transient curve. The work is in progress with this aspect.

5 CONCLUSION

In this article, a computational model supported by experimental work to thermally profile horse hoof is presented. The findings from the simulation show that by using the temperature rise curve of the heat source one can monitor the structural composition of the hoof. It is also possible to differentiate between wall separation and a fluid contained in the hoof by comparing with the transient of a normal hoof. The experimental measurement revealed the hoof structure.

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