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A new technique using roentgen stereophotogrammetry to measure changes in the spatial conformation of bovine hind claws in response to external loads

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ABSTRACT

Claw and locomotion problems are widespread in ungulates. Although it is presumed that mechanical overload is an important contributor to claw tissue damage and impaired locomotion, deformation and claw injury as a result of mechanical loading has been poorly quantified and, as a result, practical solutions to reduce such lesions have been established mostly through trial and error. In this study, an experimental technique was developed that allowed the measurement under controlled loading regimes of minute deformations in the lower limbs of dissected specimens from large ungulates. Roentgen stereophotogrammetric analysis (RSA) was applied to obtain 3D marker coordinates with an accuracy of up to 0.1 mm with optimal contrast and to determine changes in the spatial conformation. A force plate was used to record the applied forces in three dimensions.

The results obtained for a test sample (cattle hind leg) under three loading conditions showed that small load-induced deformations and translations as well as small changes in centres of force application could be measured. Accuracy of the order of 0.2–0.3 mm was feasible under practical circumstances with suboptimal contrast. These quantifications of claw deformation during loading improve understanding of the spatial strain distribution as a result of external loading and the risks of tissue overload. The method promises to be useful in determining load–deformation relationships for a wide variety of specimens and circumstances.

Introduction

During standing and locomotion, the legs of large animals are subjected to high loads resulting in three dimensional (3D) deformations in the limbs including paws, hoofs or claws. Deformations give information about internal load distribution but those in the distal leg elements are hard to quantify as they are generally small and distributed over a range of tissues and elements. As a result, our knowledge base is low and accurate predictions of which tissues can become overloaded and under what circumstances are lacking. Up to now, practical improvements (for example, in housing for dairy cattle) aiming to reduce load induced claw lesions have been mostly established through trial and error.

3D roentgen stereophotogrammetric analysis (RSA) (Selvik, 1989) is considered the gold standard for analysis of motions of rigid bodies (Tranberg, 2010) and joints (Kibsgård et al., 2012). The method is used in human medicine for precise measurements of displacements of prostheses such as stent grafts (Koning et al., 2006), knee implants (Wolterbeek et al., 2012), hip stems (Nelissen et al., 2002) and mandibular implants (Sarnäs et al., 2012). It is also used to determine the laxity of joints (Kärrholm et al., 2006), which helps to improve prosthesis design (Leardini, 2001), and in gait analysis to determine the accuracy of optical markers (Tranberg, 2010). Translations as low as 0.032 mm and rotations as small as 0.121° can be determined in kinematic studies (Kedgley et al., 2009), and even smaller deformations were determined in fracture studies (Madanat et al., 2005; Solomon et al., 2010). RSA has rarely been used in veterinary studies but, using optical markers, displacements and rotations in the distal leg of horses (Clayton et al., 1998; Meershoek et al., 2001) were significantly larger (30–40 degrees) than the accuracy that can be obtained with RSA.

Here we present an RSA technique to accurately determine load induced deformations in claws of large animals. We combined the RSA method with a force platform to determine actual loading and the point of application of the ground reaction force vector, commonly known as the centre of pressure (COP). This enabled us to correlate deformation with the actual load applied on the leg. The COP depends on claw conformation and leg stature (Van der Tol et al., 2004), and therefore could change during load experiments.

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In order to develop and test the methodology we selected a dairy cattle limb in which claw tissue damage is widespread and mechanical overload is an important risk factor for dairy cows (Bicalho and Oikonomou, 2013).

Materials and methods

In RSA, 3D positions of elements (usually radiopaque markers) are determined from two separate radiograms. In each radiogram, a spatially distributed set of body-attached markers and markers from a calibration box must be visible. The calibration box (see below) has a bottom plate with so-called '*fiducial markers*' and a top plate with control markers. The relative positions of these markers must be known precisely since the RSA software (Medis Specials, 2011) uses the projections of these markers in the radiograms to find the locations of the roentgen foci and the body-attached markers.

The experimental set-up (Fig. 1) consisted of several elements: (1) a frame for fixation and loading; (2) two roentgen systems and a cassette for obtaining the radiograms; (3) a calibration box for 3D reconstruction; (4) a force plate; and (5) the test specimen (in this case, a dissected hind limb).

The frame (see '3' in Fig. 1) consisted of a heavy foot (for stability) and a 187.5 cm high bridge on which a pneumatic cylinder ('2' in Fig. 1) was mounted and used to load the specimen. Air pressure in the cylinder could be regulated with a precision regulator combined with a manometer. The force output of the pneumatic cylinder was calibrated using two series of measurements with a metal rod placed vertically between the cylinder and the casing with supporting plate ('5' in Fig. 1).

The first series used manometer settings between 1 and 7 bar with increments of 1 bar; the second series used settings between 2 and 6 bar and increments of 2 bar. A linear regression line ($F_z = 498x - 18$, where x = manometer setting in bar and F_z = measured vertical force in N) fitted well ($R^2 = 1$) (for underlying data see Appendix: Supplementary material).

Test objects were placed on a 10 mm thick carbon fibre plate (KVE Composites Group, The Hague, The Netherlands) that protects the calibration box ('6' in Fig. 1) and roentgen cassette drawer ('7' in Fig. 1). A deflection of 2.4 mm was predicted for this plate under a centred load of 3000 N from a bending test of an unmounted test sample of the same material using basic bending equations. In the final set-up, the plate was clamped and firmly mounted in the casing, leaving sufficient space such that even after deflection it would not touch the calibration box. We assumed that clamping would significantly reduce the deflection.

Force plate

The casing was attached to a force plate ('8' in Fig. 1) with an eight-channel charge amplifier (Kistler 9253B and 9865E respectively), which recorded the load of the claws in 3D with a frequency of 10 Hz. These recordings were used to monitor the actual load applied and to calculate the location of the COP relative to the origin of the force plate.

Roentgen systems

The two roentgen tubes ('1' in Fig. 1; Philips Maximus CM100 and Philips Practix 400) were positioned approximately 1.5 m above the cassette, both at an angle of 30° to the vertical and independent of the loading frame. Both tubes were energised by manually pressing the exposure buttons simultaneously.

Images were captured on photostimulable phosphor plates (Agfa CR MD4.0 General 35 × 43 cm) and digitised (Agfa CR 35-X or Agfa CR 85-X digitizers). During exposure, a cassette was located in the drawer below the calibration box.

Calibration box

The 570 × 396 × 92 mm calibration box was constructed with top and bottom layers of 21 mm sandwich plates with foamed poly(methyl methacrylate) (PMMA) in between 1 mm carbon fibre facings and sides of 6 mm sandwich plates with foamed PMMA in between 0.5 mm carbon fibre facings (KVE Composites) resulting in a stable and radiolucent object with parallel top and bottom layers. In these layers, 1 mm tantalum markers were inserted in pre-defined spots with a CNC machine and glued with cyanoacrylate (top layer 40 control markers, bottom layer 44 fiducial markers), such that their projections surrounded those of the markers in the tested specimen.

The calibration box was mounted in the casing beneath the load bearing carbon fibre plate. Calibration of the box is described in the Appendix: Supplementary material, and showed that an accuracy of about 0.1 mm was achievable for markers throughout the detection area.

Preparation of test specimen

The system was tested by loading a bovine hind limb. The limb was obtained from a fresh cadaver brought to the Department of Pathobiology, Faculty of Veterinary Medicine, University of Utrecht, for post-mortem analysis. The animal was euthanased for clinical reasons, but did not show claw or leg disorders or infectious

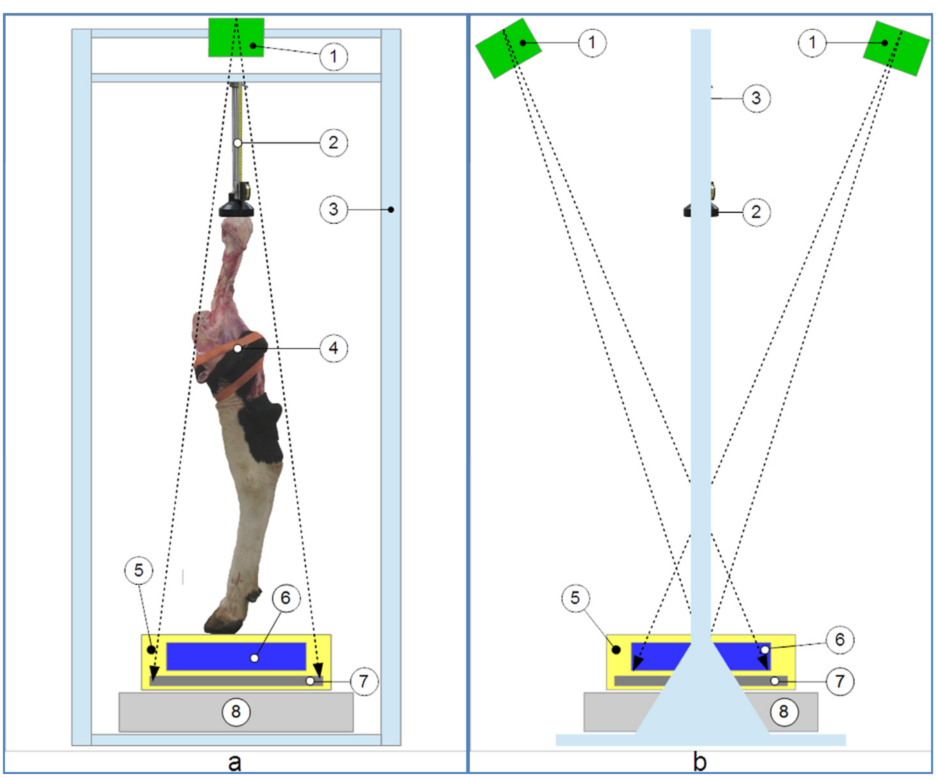

Fig. 1. Schematic representation of test equipment from two orthogonal viewpoints: (a) and (b): (1) roentgen tubes; (2) pneumatic cylinder for loading; (3) test frame; (4) tested specimen; (5) casing with supporting plate; (6) calibration box; (7) roentgen cassette drawer; (8) force plate.