Interpretive summary

Impact of Concrete Floor Roughness on Claw-Floor Contact Pressures, Franck and De Belie

Inadequate properties of floors in cattle facilities seem to be a main cause of most claw problems, resulting in economic losses and impaired animal welfare. Many claw diseases are sequels of an extreme local overload, due to the roughness of the concrete floor. Going from smooth to rough surfaces affects the pressure distribution as shown in a bovine claw model, resulting in increasing peak pressures and deformation of claw wall. Hence, when surfaces are too rough, tissue damage may be provoked that probably has consequences for the aetiology of claw diseases and subsequently might affect cows' locomotion.

CONCRETE FLOOR – CLAW MODEL INTERACTION

Concrete Floor – Bovine Claw Contact Pressures Related to Floor Roughness and the Deformation of the Claw

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ABSTRACT

The intention of this research was to study the impact of concrete floor surface roughness on a bovine claw model and to assess the deformation of the bovine claw model under load. The pressure distribution between the floor and the claw is the key method in this research. Monitoring foot-to-ground pressure distributions may provide insight into the relation between high local pressures and foot lesions. Concrete floor samples were made with 5 different finishing methods. Their roughness was determined by measuring the heights of the "peaks and the valleys" of the surface with a high-precision laser beam. The smoothest surface was the sample finished with a metal float (surface roughness $R_a = 0.062$ mm) and the roughest surface occurred with the heavily sandblasted sample (surface roughness $R_a = 0.488$ mm). The roughness of the concrete floor samples was related to the mean and peak contact pressures that can occur in a laboratory test bench between floor and bovine claw. It was found that the claw itself has approximately 2 times more effect on these contact pressures than the surface roughness. Peak pressures found were high enough (up to 111 MPa) to cause damage to the bovine claw sole horn. The strains occurring in the horn wall were measured and related to the floor-finishing method and the load. Strain gauge measurements indicated that it is difficult to predict what kind of deformation of the claw wall will occur at a certain location. Different strains will occur for different floor-finishing methods. The corresponding stresses in the horn wall did not exceed the yield stress (14 and 11 MPa for dorsal and abaxial wall horn, respectively).

Key words: "bovine claw", "concrete floor", "roughness", "pressure distribution"

INTRODUCTION

In this paper, we tested the hypothesis that rougher floors would result in higher contact pressures. Lameness in cattle is widely recognised as a major economic and welfare problem (Vermunt and Greenough, 1996). A wide range in the prevalence of lameness in dairy cattle is encountered; this variation may be due to a combination of many factors, including breed types, genetic selection, conformation characteristics, nutrition and feeding practices, amount of milk production, manure handling systems, presence or absence of certain types of infectious disease, and factors related to the environment in which dairy cows are kept (Cook et al., 2004). The dairy cow's environment, in particular the type of flooring surface, may be the main determinant of the degree of lameness (Cook et al., 2004). Lowering the prevalence of claw disorders and incidence of lameness in current housing systems requires more insight into characteristics of the floors that are involved (Somers et al., 2003).

In modern farms, cattle are almost always housed on full concrete floors or on prefabricated slatted concrete floors because of the many advantages including durability and cost-effectiveness. Despite these advantages, 80% of the cows exposed to concrete flooring are affected by 1 or more claw disorders concurrently. Cows housed in straw yard systems have the lowest levels of claw disorders, a marked contrast to concrete flooring (Somers et al., 2003). Solid concrete floors yield numerically higher prevalence of claw disorders (5 out of 9 tested) than slatted floors, but differences were not significant (Somers et al., 2003).

Animals often show claw diseases that could be the direct and indirect effects of the roughness and slipperiness of the floor (McDaniel and Wilk, 1991). Many claw diseases are caused by traumas of the dermis of the sole, resulting from extreme local overload (Distl and Mair, 1993). It is believed that the processes of normal horn production and abrasion are disturbed by abnormal load bearing on a hard floor. This could result in claw malformation (van der Tol et al., 2002). Increased growth rate of the horn can occur with (free-stall) housed cattle (Vermunt, 1996) and the wear rate often exceeds the rate of claw horn growth (Shearer and van Amstel, 2003). Confinement on concrete enhances the physical effects of excessive load bearing on hooves. These physical effects are further complicated by the fact that the unyielding nature of hard-flooring surfaces tends to irritate the corium, thereby increasing its blood flow and accelerating the growth of claw horn (Shearer and van Amstel, 2003). Somers et al. (2005) confirmed that cows in straw yards had smaller lesion scores for digital dermatitis than cows housed on solid or grooved concrete floors. Moreover, the claws of cows on solid concrete floors were steeper than those held on slatted and grooved floors (Somers et al., 2005).

A better understanding of the consequences of using concrete floors on dairy cattle claws and the causal relation and interaction with claw problems, will result in better-designed floors and improved animal welfare. The pressure distribution measurement between the floor and the claw is the key method in this research. Monitoring of foot-to-ground pressure distributions may provide insight in the relation between high local pressures and foot lesions.

Different researchers have investigated the kinetics of the equine limb and have recorded the ground reaction forces. Few similar studies have been performed on cattle. Sato et al. (1988) measured the forces applied by cow hooves during walking; Sato and Hasegawa (1993) examined forces during standing and lying; and Albutt et al. (1990) determined the forces during walking, together with horizontal foot movements. In those studies, a force plate was used to register the force components in 3 perpendicular directions. However, measurement of the contact pressure distribution or determination of the influence of the floor surface was not possible with that system because the force plate used recorded only the vertical reaction force and the duration of the contact. Distl and Mair (1993) did succeed in registering the pressure distribution under claws of living cattle using a force sensor consisting of small individual plate capacitors (although with a limited resolution: 4 sensors/cm^2). Nevertheless, they were also limited to the measurement of pressures between claw and measuring plate (instead of claw and floor). This implies that their equipment did not allow investigation of the effect of the floor surface properties. The foot-to-ground pressure distribution was also described in more recent literature (van der Tol et al., 2004; van der Tol, 2004; Carvalho et al., 2005), but again, the influence of the floor roughness was not taken into account because the bovine claws were tested on metal pressure plates, sometimes covered with rubber mats.

In this paper, the determination of the roughness of concrete floors and the assessment of contact pressures between claw and concrete floor is presented. These findings are further elaborated with the study of the strains and stresses in the claw wall horn; strains were recorded with strain gauges. The influence of floor roughness on abrasiveness or slip-resistance is beyond the scope of this paper.

The approach of measuring contact pressures between cattle claws and different concrete floors in a laboratory test bench was first discussed by De Belie and Rombaut (2003). Their experiments served as the basis for the current research (e.g., the same concrete samples were used and the same loading steps were applied). In the current research, the methods were refined (e.g., the claw preparation was more practical and the laser measurement device was equipped with stepping motors and better software to enhance the accuracy and repeatability of the roughness measurements).

It was expected that concrete floors with a greater degree of roughness would result in higher contact pressures, perhaps high enough to cause damage to the bovine claw. This theory was tested by pressing bovine claw models on concrete samples with different roughness and by measuring the occurring contact pressures in the meantime.

MATERIALS AND METHODS

Concrete panels

Five samples of concrete floors (160 mm long × 160 mm wide × 50 mm high) were made with 5 different kinds of surface structure, obtained by varying the finishing method: surfaced with a metal float (**metal**), surfaced with a wooden float (**wood**), brushed (**brush**), and mildly (**sand 1**) and heavily (**sand 2**) sandblasted. The latter 2 were included to simulate a degraded concrete floor with coarse aggregates protruding. The same mix composition of concrete (i.e., same aggregates, same ratios of components) was used for all samples.

Roughness measurement of concrete panels

The roughness of the concrete floors was determined by measuring the height of the surface peaks and valleys with a high precision laser beam (sensor ILD 1800-50 and interface optoNCDT 1800, Micro-Epsilon Messtechnik GmbH, Ortenburg, Germany; resolution = 5 μm), mounted on an automated laser measurement (**ALM**) table developed in-house and equipped with 2 stepping motors controlling the motion in the X and Y directions (Figure 1).

The profile measurements can then be used to calculate the centre-line roughness value (**R_a**), the root mean square roughness value (**R_q**), and the difference between the mean of the 5 highest values and the mean of the 5 lowest values (**R_z**) values according to the standard BS 1134 (British Standards Institution, 1972). The R_a value, or centre-line value, is determined with an average line drawn through the measured profile; R_a is then the sum of the surface areas between the profile and the centre-line over a selected reference length, selected to include important roughness features, but exclude errors of form. Using the ALM, the R_a value can be determined with an accuracy of 7 μm. The R_q value is equal to the standard deviation of the roughness height distribution (British Standards Institution, 1972), and the R_z value is the difference between the mean of the 5 highest values and the mean of the 5 lowest values (van Beek, 2004).

For all samples, 12 profiles in the centre of the concrete panel were measured with reference lengths of 40 mm (Figure 2). With this reference length, slopes and waves due to errors of form needed to be filtered out. The sampling frequency was 43 measurements/mm in the X direction and 52 measurements/mm in the Y direction as shown in Figure 2.

Bovine claw preparation

Twenty limbs of freshly slaughtered cows were taken from the abattoir. Most cows (80 %) were beef cows from the Belgian Blue Beef breed and were almost all held on slatted floors, some dairy cows (Holstein, 20 %) were used. No distinctions were made between fore and hind limbs or between left and right limbs. Mostly front limbs were taken because the cows were hanging in the abattoir attached to a hind limb (thus, it was easier to cut off the front limb). Although it is generally accepted that the lateral hind claws are most prone to claw lesions (Weaver et al., 1981), this higher susceptibility can be explained by the different loading situation, not by the different mechanical properties of bovine claw horn from hind and fore claws. The lateral hind claws undergo a highly fluctuating load during continuously occurring small left-right movements, because the hind limbs are connected to the body with hinge joints, unlike the fore limbs (Toussaint Raven et al., 1977). In a static loading situation, as simulated in the described laboratory tests, a distinction between fore and hind limbs would therefore not be necessary. In earlier research (Franck et al., 2006), the variables fore vs. hind and left vs. right did not have any significant effect on the biomechanical properties of the claw horn, such as the modulus of elasticity, the coefficient of Poisson, and the yield stress.

The claws all had well-formed healthy and intact horn walls and soles (without damage or disorders). All limbs had undergone the same treatment: they were cut off the just-slaughtered animal, cleaned (i.e., the slurry was scraped off), and immediately put in plastic bags to maintain the moisture level. The limbs were then frozen until further preparation. In the frozen state, the claws were sawn off just above the horn wall, with the saw cut parallel to the sole, immediately before testing. The claw was then thawed to enable the 2 toes to be manipulated (to be positioned at the same level). The unfrozen claw was put in a polyvinylchloride (**PVC**) tube (i.d. = 150 mm; height = 120 mm) with the sole of the claw making close contact with a horizontal surface. A layer of liquid plaster (to a height of ±20 mm) was poured into the PVC tube so that the plaster was surrounding the claw. After the plaster dried completely, epoxy resin was poured on the claw and the plaster. The purpose of the plaster was so that the epoxy resin would not interfere with the sole and the lower parts of the horn wall (epoxy resin cannot be removed easily); the epoxy resin was used to confine the whole claw in a solid block that could then be used to transfer forces onto the claw. Inert quartz filler was added to the resin to be able to dissipate the heat generated by the 2-component exothermic reaction. After the epoxy resin had cured, the PVC tube and the plaster were removed. The procedure was repeated for each claw until 20 claws were prepared as shown in Figure 3.

Claw-floor contact pressure distribution

The roughness of the floor was examined relative to the contact pressures that occur between cattle claw and concrete floor. The contact pressures and the pressure distributions were studied by pressing a well-formed bovine claw, embedded in epoxy resin (Figure 3), onto the concrete samples in a hydraulic compression machine. All 20 bovine claws with various shapes were used for contact pressure measurements. The test setup is illustrated in Figure 4. Only 1 claw was tested at a time and each claw was consecutively tested for all load steps on all floor samples.

The surface of the epoxy resin was parallel with the sole of the claw. This was done to transfer the load of the hydraulic testing machine to the sole of the claw uniformly.

A thin film (0.1-mm thickness) consisting of several electronic sensors was placed between the bovine claw and the concrete sample to record the pressure distribution. The sensors (Tekscan 5101, Tekscan Inc., South Boston, MA, USA) had a surface of 112 × 112 mm, with 15 pressure sensors/cm^2.

Before testing with a bovine claw, the sensors were calibrated by matching the load registered by the sensors to the load shown by the hydraulic compression machine for a selected load value of 24 kN, applied on a calibration cylinder. The calibration cylinder consisted of Ertalon 6 SA (Quadrant AG, Zürich, Switzerland), a viscoelastic polymer material, and had a diameter of 80 mm.

The sensors generate a nearly real-time image of the contact pressures on the computer screen by means of dedicated software (I-Scan, Tekscan Inc.). A gradual increase of the vertical load (2 to 9 kN, in steps of 1 kN) was applied by means of the testing machine. For each discrete load step, the colour-coded contact image (Figure 5) and variables such as contact surface, mean contact pressure, and peak contact pressure were recorded.

The load read from the hydraulic compression machine and the contact surface provided by the sensors were used to calculate the mean contact pressure. This calculated contact pressure was then compared with the mean contact pressure provided directly by the sensors. The ratio between the 2 mean contact pressures thus obtained resulted in a correction factor. The peak contact pressure values provided by the Tekscan sensors were afterwards multiplied by that correction factor. This was an extra calibration based on real measurements.

A typical image provided by the Tekscan sensors and visualised by the software is shown in Figure 5. Unfortunately, the outline of the claw cannot be shown because it was not recorded by the sensors and because the Tekscan sensors have no reference to X/Y coordinates.

Strain measurements on claw wall horn

For 4 bovine claws, the wall horn strain under increasing load was monitored. Linear strain gauges (HBM 6/120LY16: 6 mm × 2.8 mm Constantan measuring grid, 6-mm measuring length and resistance of 120 Ω, Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany) were attached with 2-component cyanacrylate glue to the horn wall in both vertical and horizontal directions. There were 2 strain gauges on the dorsal wall and 2 on the abaxial wall

(1 on each toe; Figure 6). The test setup was the same as that used for contact pressure measurements (Figure 4). The load applied varied between 2 and 9 kN, in steps of 1 kN.

The location and the direction of the strain gauges on the right and left toes of the 4 claws is indicated in Figure 7. The strain was then related to the load applied on the claw and with the finishing method of the floor sample. The measurements generated by strain gauges on homologous locations on different claws were compared: the measurements of strain gauge 1 of the claws 1, 2, and 4; the measurements of strain gauge 2 of the claws 1 and 3; the measurements of strain gauge 3 of the claws 1 and 3; and the measurements of strain gauge 4 of the claws 1, 2, and 3 were compared with each other (see Figure 7). If mirror symmetry between the 2 toes is assumed, then more series of measurements can be compared with each other: strain gauge 2 and 3 of claw 2 and 4; strain gauge 4 of claw 1, 2, and 3 and strain gauge 1 of claw 3; strain gauge 2 and 3 of claw 1 and 3; and strain gauge 1 of claw 1, 2, and 4 and strain gauge 4 of claw 4.

Statistical analyses

The statistical analyses were carried out with the software package SPSS 12.0 for MS-Windows (SPSS Inc., Chicago, IL, USA). Two types of ANOVA were performed for 1 dependent variable: the first analysis was to test only 1 factor at a time and the second analysis tested the effects of more than 1 factor (and their interactions) at a time. The first is a 1-way ANOVA and the other is a univariate GLM. Significance levels were always kept at $\alpha = 0.05$. Appropriate posthoc (e.g., Student-Newman-Keuls) tests were also carried out.

RESULTS

Roughness measurement of concrete panels

The mean of the roughness measurements (reference length = 40 mm) is illustrated in Figure 8. The surface finishing had a significant effect on the roughness of the concrete panels. There was an increase in roughness with the panels in the following order: metal, wood, brush, sand 1, and sand 2.

The Student-Newman-Keuls test ($\alpha = 0.05$) was used to calculate the probability that results with similar mean values are not significantly different. This test showed that brush and sand 1 finishing methods could not be distinguished from each other with regard to their surface roughness variables.

Claw-floor contact pressure distribution

A univariate GLM proved that load, claw, surface finishing, and the interaction of claw with surface finishing all had a significant effect ($\alpha = 0.05$) on contact area, mean contact pressure, and peak contact pressure.

An 1-way ANOVA for the quantitative dependent variables contact area, mean contact pressure, and peak pressure by the single variables claw, load, and surface finishing was performed. This proved that claw, load, and surface finishing had significant effects ($\alpha = 0.05$) on contact area and peak contact pressure. Claw and surface finishing also had significant effects on the mean contact pressure, but load did not have a significant effect on mean contact pressure. This is because the contact area became larger with an increase in load, due to deformation of the claw.

The magnitude of the effect of the different variables is summarised in Table 1; the effect of the floor surface finishing was set as the reference value (= 1).

The results of the peak contact pressures can be illustrated with the graphs in Figure 9. The graph that shows the effect of surface finishing on peak contact pressure indicates that the values for sand 2 were remarkable higher than the results for the other surface finishes. Indeed, when the results of sand 2 samples were removed, there was no significant effect of surface finish on the peak contact pressures. The sand 2 finish yielded greater surface roughness values than did the other finishes. The mean values of the peak contact pressures matched the roughness values almost perfectly: the Pearson correlation ρ between R_a and the mean values of the peak contact pressures was equal to 0.987.

In Tables 2 and 3, the values for contact area (mm^2), mean contact pressure (MPa), and peak contact pressure (MPa) are shown for loads of 2 and 6 kN, respectively. These load values represent a physical meaning: 2 kN approximates the weight of a cow on 1 limb when standing or walking, 6 kN approximates the weight of a cow that is exerted on 1 limb that can occur when the animal is running or jumping.

The results in Tables 2 and 3 show that the increased load mainly had an effect on the contact area; the mean and peak contact pressures were less affected. The mean contact area nearly doubled in value with a load increase from 2 to 6 kN.

Strain measurements on claw wall horn

Strain gauge readouts indicated elongation and shortening at a particular region of the claw wall. Negative strain gauge readouts indicated a shortening of the claw wall and positive measurements indicated that the horn wall became elongated. Sometimes a transition took place: the horn wall first elongated (+) and then shortened (-) or vice versa with increasing load put on the claw. Figure 10 illustrates the different slopes of the strain vs. load curves of claw 1 on a metal-finished concrete panel. Gauge 4 passed from elongation to shortening at around 5 kN.

A 1-way ANOVA was run to compare the readouts of strain gauges at the same location and with the same direction. Significant differences ($\alpha = 0.05$) were found between following series of measurements: with strain gauge 3 between claws 1 and 3 for surface finish sand 2 and with strain gauge 4 between claws 1, 2, and 3 for all finishes. For the finishes metal, wood, and brush, significant differences were found between claw 1 and 3 and between claw 1 and 2. For the finishing methods sand 1 and sand 2, significant differences were found between claws 1, 2, and 3. These findings were supported by the Student-Newman-Keuls test. Before conducting the tests, no significant differences were expected because the strain gauges were placed on the horn wall in the same direction and on the same location. Another ANOVA was run in order to check for significant differences between strain gauge readouts when mirror symmetry was assumed. The following significant differences were found: with strain gauge 2 and 3 of claws 2 and 4 for all finishing methods; with strain gauge 4 of claws 1, 2, and 3 and strain gauge 1 of claw 3 for all finishing methods; and with strain gauge 2 and 3 of claws 1 and 3 only for sand 2.

The position of the point of action of the load on the claw provides an explanation for the differences between the strain readouts at the same location and with the same direction, also in case of mirror symmetry. The general observations for different floor finishing methods are summarised in Figure 11.

The arrows next to the strain gauges indicate whether elongation or shortening occurred in the horn wall in that particular location. The transition is indicated with dotted lines. The thick arrow on top of the claw indicates the point of action of the load (centre of force), which was also determined with the I-Scan software. For 3 out of 4 claws, the point of action changed during the loading of the claw; this is also shown in the claw schemes with an arrow indicating the travel of the point of action, which occurred predominantly from left to right. Due to irregularities of the claw and imperfections of the claw sole, it was not always possible to exert the load in the centre of gravity of the claw. Moreover, in real circumstances, the cow moves and the point of action for every limb changes continuously.

DISCUSSION

Although locomotory problems are complicated and multifactorial, this paper mainly deals with animal housing. The emphasis is on the concrete floor, with the focus on the roughness of the floor. The intention of this paper was to investigate the influence of floor roughness on contact pressures only, not on abrasiveness. Abrasiveness is also an important factor but beyond the scope of the current paper.

Roughness measurements

The ratio of the variables R_q/R_a was equal to 1.21, which is in accordance with the ratio (1.25) found by van Beek (2004). This means that the roughness was according to a normal distribution. The ratio R_z/R_a was equal to 4.7; van Beek (2004) reported values between 4 and 7 for this ratio.

Surface roughness of concrete floors was previously addressed in literature. Braam and Swierstra (1999) described the surface roughness of differently finished concrete floors. Two finishing methods can be compared with finishing methods described in this study: finishing with a plastic float trowel (metal) and brushed with a broom (brush). The ranges for R_a values for a surface finished with a plastic float trowel (0.080 to 0.145 mm) and the brushed surface (0.090 to 0.160 mm) are comparable with the results of the current study (ranges: 0.036 to 0.124 mm and 0.127 to 0.326 mm, respectively).

The obtained results for surface roughness are different compared with measurements on the same panels in De Belie and Rombaut (2003): in the current research, the roughness values are consistently lower (except for metal), with less variation for sand 1, and significantly higher for sand 2 compared with the other surface finishing methods. The differences are probably due to the improvements made to the ALM, allowing more precise measurement through the introduction of stepping motors (fixed amount of samples per millimetre). Moreover, other regions on the concrete samples might have been measured, and the measurements in De Belie and Rombaut (2003) were performed with a reference length of 50 mm (vs. 40 mm in the current research).

Surface roughness affects the locomotion of cattle positively as well as negatively, by improving frictional properties and reducing slipperiness, and by increasing wear rates of claw horn, which leads to a less protruding wall, thin soles, and thus lameness (Bonser et al., 2003). Many farmers roughen the floors to reduce slipperiness, but this may increase the risk of claw disorders by creating high pressures that may damage the bulb. The remedy may be worse than the initial problem in this case.

Floors that optimise welfare should be sufficiently abrasive to prevent slipping; the rates of abrasive wear should not exceed and preferably equal rates of claw horn growth (Bonser et al., 2003). It appears that surface roughness is the main factor in mediating friction, although the hydration state of the claw material plays an important role on hoof attrition rates. Preliminary data hinted at complex interactions between the moisture content of claw horn, frictional properties, and abrasive wear (Bonser et al., 2003).

Although no roughness values are available for comparison, Phillips and Morris (2001) described the frictional and abrasive characteristics of 4 different surfaces (concrete covered with epoxy resin, with and without aggregates of different size). The floor types with the smallest aggregates (0.5 mm) may resemble some concrete panels used in the current research, such as wood and brush. The floor with the 0.5-mm aggregates seemed to be most suitable for cows to walk comfortably (cows were taking long strides) with little risk of slip. Rougher floors (aggregates of 1.2 and 2.5 mm) yielded higher abrasion rates, which could result in sole bruising (Phillips and Morris, 2001).

Somers et al. (2003) found that cows exposed to concrete flooring had significantly more claw disorders than cows housed in straw yard systems. This difference could be explained by the roughness and the abrasiveness of concrete floors.

Claw-floor contact pressure distribution

The measured peak contact pressure for all loads varied between 2.2 MPa and 110.7 MPa. The latter value was well beyond the yield stress of bovine claw horn that was determined by Franck & De Belie (2004) and Franck et al. (2006). The yield stress at the physiological moisture content (approximately 30%) was 14.3 and 10.7 MPa for dorsal and abaxial wall horn respectively (3-point bending test), and 56.0 MPa for sole bulb horn (compression test applying a uniform load on a sample with surface area of 100 mm^2 and height of 4 mm). These results prove the hypothesis that states that rougher floors can result in higher contact pressures that can damage the claw horn.

The contact area increased with increasing force applied on the claw, but the mean contact pressure also increased with increasing force. This means that the contact area increased less in proportion to the increase of the force applied on the claw. It is interesting that the contact area increased, which may be explained by the deformation of the claw (which was more substantial at a higher load). The peak pressure increased at a faster rate than the mean contact pressure. However, the rates of increase in contact area, mean contact pressures, and peak pressures were different for every claw.

The surface finish resulting in the highest peak contact pressure also differed for various claws. The least rough surface did not always result in the lowest mean and peak contact pressures and the roughest surface did not necessarily result in the highest mean and peak contact pressures. This is illustrated in Figure 12: the metal surface finishing method resulted in the smoothest surface, but sand 1 and wood resulted in consistently smaller peak contact pressures for loads between 3 and 9 kN for this particular claw.

For the same applied force, the contact area was lower with rougher surfaces. This was especially the case for sand 2 surfaces. On that surface, the aggregates were clearly visible and the bovine claw was only supported by these aggregates, resulting in a very small contact area. An example may illustrate these findings: claw 8 loaded with 6 kN yielded a contact area of 2,013 mm^2 on a sand 1 surface and a contact area of only 948 mm^2 on a sand 2 surface.

The maximum contact pressures reported by De Belie and Rombaut (2003) were of the same order of magnitude, but the effect of the factor claw was larger in the current research, in which claws of 20 cows instead of 3 were tested. Because the claw itself has the highest effect on the contact pressure measurements, this factor alone could be responsible for the differences between the results of the 2 studies.

Not only roughness, but also the geometry or the structure of the floor (e.g., slatted vs. solid) may cause overload of the claw. Nilsson et al. (2002) investigated contact pressures on slatted floors. It was expected that a solid floor would result in a more even pressure distribution than a perforated one. Preliminary measurements showed that the contact pressures indeed might increase considerably (+40%) when a slatted floor is used (the claw was placed transverse to the slot of the slatted floor). However, this was a very preliminary result because only 1 claw was tested. Our preliminary tests with 4 cattle claws (the same as those tested on the other panels) on a polished slatted floor (slat width of 40 mm) showed no significantly higher contact pressures than on any solid floor. Of course contact pressures on slatted floors might depend highly on the way the slat edges are finished. Somers et al. (2003) stated that the prevalence of claw disorders was numerically but not significantly higher on solid floors than on slatted floors.

The values for contact area and mean and peak contact pressures determined in this study are only valid for a square-standing animal or for a walking cow during the stance phase with full contact between claw and floor. For these circumstances, van der Tol et al. (2002) found values between 0.17 and 0.54 MPa as maximum pressures between cattle claw and pressure plate. In a later study, van der Tol (2004) found higher maximum pressures of 1.24 MPa for forefeet and 0.89 MPa for hind feet of standing-still cows supported by all 4 feet. The maximum peak pressure (1.24 MPa) found by van der Tol (2004) and the minimum peak pressure found in this study (4.8 MPa) differ by a factor of 4. The dairy cows in van der Tol's study had a weight of 6.9 ± 1.3 kN, which means that a weight of about 1.7 kN was exerted on 1 limb. These values have to be compared with the values found at 2 kN in the current study (Table 2). The minimum mean contact pressure was in this case 0.60 MPa, which is of the same order of magnitude as the results in the van der Tol (2004) study, but the maximum mean contact pressure for the smoothest surface (metal) was 19.91 MPa. The difference in results is partly due to the shape of the claw itself. The claws of the cows used in van der Tol's study (2002) were trimmed 3 or 5 wk before the experiment, which means that the contact area increased, which led in turn to a pressure decrease. In addition, a rubber mat was used, which further increased the contact area or at least smoothened out the pressures recorded. The difference in sensor resolution could have contributed to the difference between the results: the force plates used in the van der Tol study (2004) had a resolution of 2.6 sensors/cm^2, whereas the Tekscan sensors used in this study have a resolution of 15 sensors/cm^2. In our research, the measured contact pressures occurred between claw and concrete floor, instead of between claw and force plate. In fact, the Tekscan sensor mats were draped over the rough concrete surface, so they were subjected to compression and to some bending. The sensor mat could have registered forces that were not entirely perpendicular to the surface, but in this case, the recorded pressures would be smaller because only the component of the force perpendicular to the sensor mat was recorded. The Tekscan sensors are appropriate (high resolution) for this kind of test, as indicated by an earlier study (De Belie and Rombaut, 2003).

Strain measurements on claw wall horn

The strain observations between different finishing methods cannot be compared exactly because the point of action of the load would never be at exactly the same position because the concrete panels had to be swapped and the bovine claw had to be repositioned. The results should be interpreted with care when mirror symmetry was assumed. There might be anatomical symmetry, but in reality, forces are not equally shared between the lateral and medial claws of 1 limb (Toussaint Raven et al., 1977; van der Tol et al., 2002).

Loading can deform the claw in various ways, depending on the point of action of the load, and in reality, the claws are loaded in different ways. If the hind claws, especially the lateral hind claws, suffer from claw diseases, then that might also be due to the direction of the load. The hind legs of the cow are connected to the pelvis through a ball-and-socket joint at the hip. During movement, the distribution of weight within and between the claws changes, displacing more weight to the lateral claws (Toussaint Raven et al., 1977). The point of action of the load can also change due to overgrowth of the claws (e.g., overgrowth of abaxial wall or at the toe), which can increase the potential of a sole ulcer to occur (Shearer and van Amstel, 2003).

The stress in the claw wall, σ (N/mm^2), is related to the strain ε:

$$\sigma = \varepsilon \cdot E$$

where E is the modulus of elasticity of wall horn (N/mm^2). To assess the risk on wall-horn rupture, the strain occurring at a load of 6 kN on floor type sand 2 can be multiplied by the modulus of elasticity found in earlier research (Franck et al., 2006); when a loading velocity of 1 mm/min is assumed, the modulus of elasticity was 382 and 261 N/mm^2 for the dorsal and abaxial horn wall, respectively. Strain gauges 1 and 4 are attached to the abaxial horn wall and strain gauges 2 and 3 are attached to the dorsal wall. The resulting stresses can then be compared with the yield stress found in earlier research (Franck et al., 2006). The results are summarised in Table 4. The calculated stress values do not exceed the yield stresses of 14.3 and 10.7 N/mm^2 for dorsal and abaxial wall horn, respectively, as measured in earlier research (Franck et al., 2006).

General issues

The results presented in this paper come from a prepared claw cut from a frozen limb just above the coronary band parallel to the sole, which was solidly assembled in an epoxy resin block that could be mounted on a test bench. There are limitations to this test setup because the in vitro claw can hardly be recognised as a natural claw. It lacks the dynamics of the claw in vivo like the ligamenteous action, muscle action via tendons attached to the claw, or the navicular bone. In vivo forces while standing are mainly applied via the skeleton to the claw capsule or, in case of a sunken claw bone, also to the sole/bulb area. The relative motion of the 2 digits in vivo is quite large and this could provide a stable claw-floor contact of each single claw. These in vivo dynamical properties are not accounted for in the current bovine claw model and the acquired results could therefore be different than the stresses occurring in real circumstances. We first tried to work with a bovine limb cut off just above the metatarsus/metacarpus, but it was impossible to load this limb in the available compression machine. The claw had to be supported to prevent it from jumping out of the machine (which is very dangerous); such a support also would have affected the measurements (the motion of the limb had to be restricted). Embedding the bovine claw in epoxy resin also presented some drawbacks. The resin embedded the claw in a monolithic block, so movement of the 2 toes was restricted, which was a simplification of reality. This method represents a square-standing cow with the sole perfectly set on the floor. It was an easy and straightforward way of performing contact pressure measurements.

Another possible issue with the test method was that all claws were loaded several times on the 5 samples of concrete. If the pressure were increased beyond the compressive breaking strength of bulb horn, one could argue that the horn structure would be changed and the next measurement would be performed with a claw with slightly damaged (functional) morphology. The testing of the claws was not randomly performed; the claws were consecutively loaded from 2 to 9 kN and each cycle was repeated on different concrete samples. However, the compressive breaking strength of bulb horn was only achieved in certain small areas of the claw, so the authors judged that consecutive loading did not pose a major issue. The resin block transferred the loads on the claw; not only on the bone, but also via the claw wall (the pressures were distributed over the claw).

CONCLUSIONS

Peak contact pressures that were well beyond the yield stress of the bovine claw sole horn were measured between cattle claws and concrete floors of varying roughness. Pressures beyond the yield stress mean that the claw sole horn can indeed be damaged in real circumstances. On the other hand, claw wall stresses did not exceed the corresponding yield stress. The roughness of the floor played a role in the claw-floor contact area, mean contact pressure, and peak contact pressure, but the effect of the claw itself was greater. Strain gauge measurements indicate that it is difficult to predict what kind of deformation of the claw wall will occur at a certain location. For different floor finishing methods, different strains will occur. Under increasing load, deformation can pass from elongation toward shortening or vice versa, depending on the change in point of action of the load.

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TABLES

Table 1. Results of a univariate GLM for the effect of the variables claw, load, and surface finishing, and the interaction between claw and surface finishing on contact area, mean contact pressure, and peak contact pressure[1]

Variable	Contact area	Mean pressure	Peak pressure
Load	7.88	0.57	1.77
Claw	1.51	2.11	1.97
Surface finishing	1.00	1.00	1.00
Interaction claw/finishing	0.03	0.12	0.08

[1] The variables claw and surface finishing were considered as fixed-effect factors; the variable load was considered as a covariate. Effects are significant ($\alpha = 0.05$) and are presented relative to the effect of floor surface finishing, which was set as a reference.

Table 2. Measured results for contact area and mean and peak contact pressure at a load of 2 kN, which represents the weight of a cow on 1 limb when standing or walking

Variable	Mean	SD	Minimum	Maximum
Contact area, mm^2	1,196.1	849.4	65	3,316
Mean contact pressure, MPa	3.35	4.06	0.60	30.77
Peak contact pressure, MPa	15.19	15.15	2.22	87.74

Table 3. Measured results for contact area and mean and peak contact pressure at a load of 6 kN, which represents the total weight of a cow that is exerted on 1 limb

Variable	Mean	SD	Minimum	Maximum
Contact area, mm^2	2,393.8	1,374.3	297	5,381

Mean contact pressure, MPa	4.07	3.67	1.12	20.20
Peak contact pressure, MPa	21.93	21.70	3.65	99.33

Table 4. Strain and stress occurring in different strain gauges attached to the wall horn of bovine claws standing on heavily sandblasted concrete under a normal load of 6 kN[1]

Claw	Strain at strain gauge, 10^{-6} m/m				Stress at strain gauge, N/mm^2			
	1	2	3	4	1	2	3	4
1	4488	833	-1561	-361	1.17	0.32	-0.60	-0.09
2	/	-28	636	5134	/	-0.01	0.24	1.34
3	2275	1070	928	1107	0.59	0.41	0.35	0.29
4	5424	95	441	7472	1.42	0.04	0.17	1.95

[1] Strain gauges 1 and 4 were attached to the abaxial horn wall and strain gauges 2 and 3 were attached to the dorsal wall. The strain was measured and the stress was calculated using the modulus of elasticity as determined in Franck et al., 2006.

FIGURES

Figure 1. The automated laser measurement device with stepping motors (bottom and right) and concrete floor samples on the test bed.

Figure 2. Positioning of the profiles on the concrete floor samples. The profiles are shown as double-arrowed lines. With a reference length of 40 mm, slopes and waves due to errors of form needed to be filtered out. The sampling frequency was 43 measurements/mm in the X direction (intersections 1, 2, and 3) and 52 measurements/mm in the Y direction (intersections 4, 5, and 6).

Figure 3. Bovine claw embedded in epoxy resin. Plaster was surrounding the bottom part of the claw and served as a barrier for the epoxy resin. The plaster was later removed, although the remains are still visible.

Figure 4. Tekscan sensor between bovine claw and concrete panel in compression machine. The sensor is inserted in a handle, which in turn is connected to the data acquisition card of a personal computer.

Figure 5. Contact image of a bovine claw – front of the claw is on top (surface area = 3,535 mm^2, load = 5,319 N, legend in MPa). The arrow indicates the place where the highest contact pressure between claw and concrete floor occurred.

Figure 6. Strain gauges (1 to 4) glued to claw wall horn for hoof preparation number 17. Strain gauge 1 is most to the left and strain gauge 4 is not visible.

Figure 7. Location and direction of the strain gauges on left and right toes of 4 bovine claws (claws 1 to 4 are shown from left to right)

Figure 8. Roughness (R_a, R_q, and R_z) of concrete floor samples with different surface finishing (error bars: 95% confidence interval for mean). R_a is the centre-line roughness value, R_q is the root mean square roughness value, and R_z is the difference between the mean of the 5 highest values and the mean of the 5 lowest values.

Figure 9. Global results for peak contact pressures, related to the load, the claw and the floor finishing (n = 800: 20 claws × 8 load steps × 5 finishing methods; error bars: 95% confidence interval for mean).

Figure 10. Strain gauge measurements related to the applied load (claw number 1 on metal surface finishing).

Figure 11. Visualization of the sign of strain gauge readouts.

Figure 12. Peak contact pressure related to the applied load (case claw number 8).

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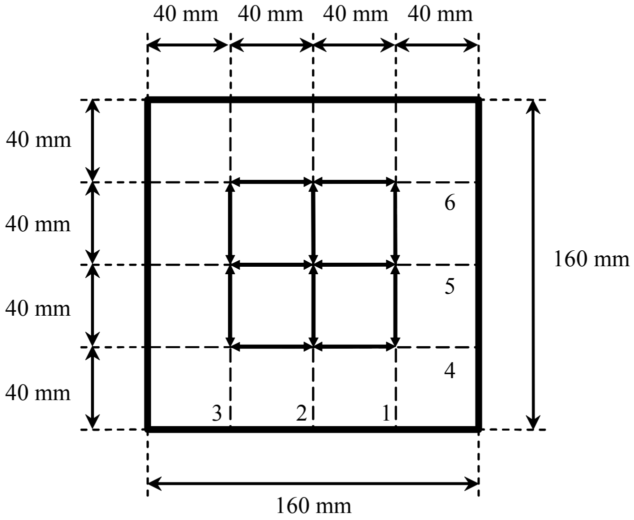

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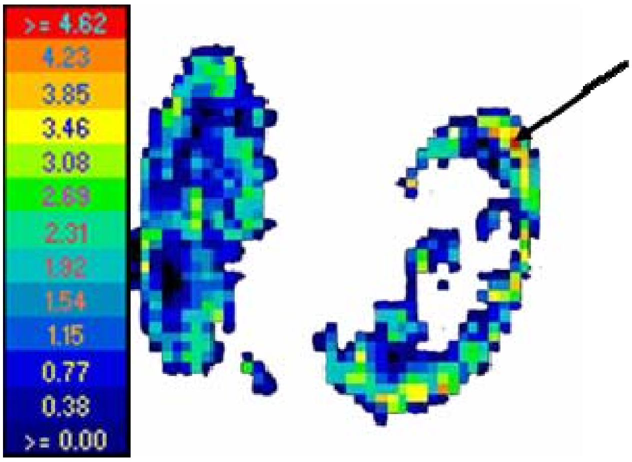

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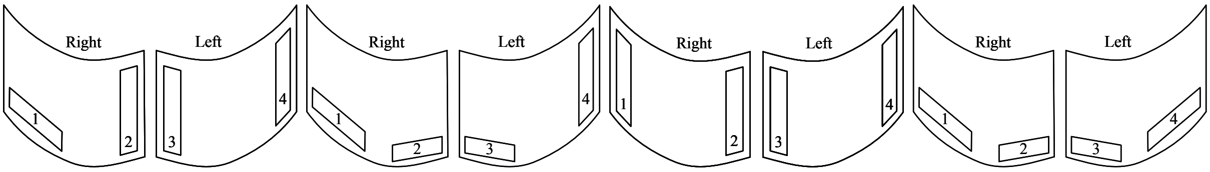

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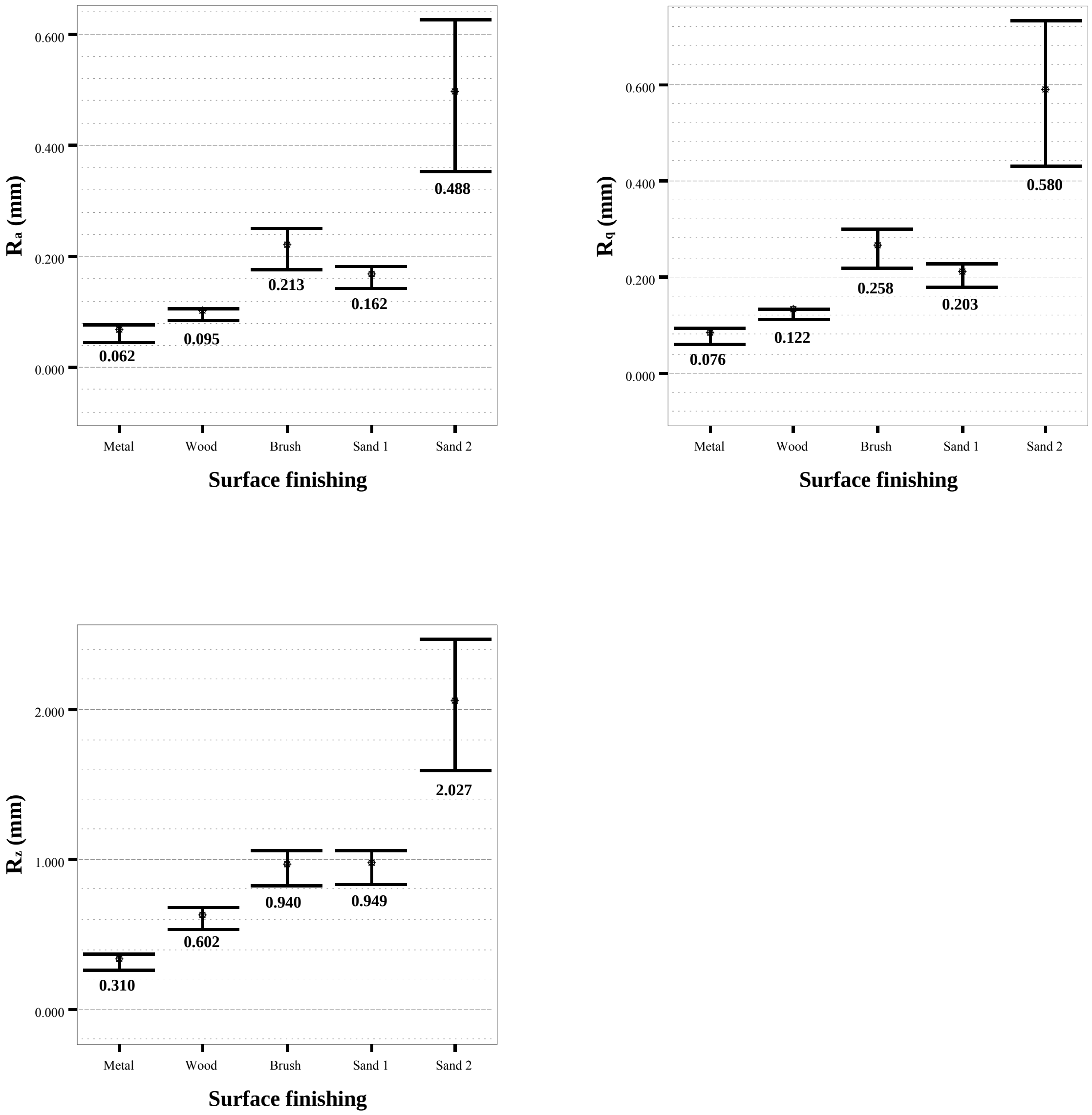

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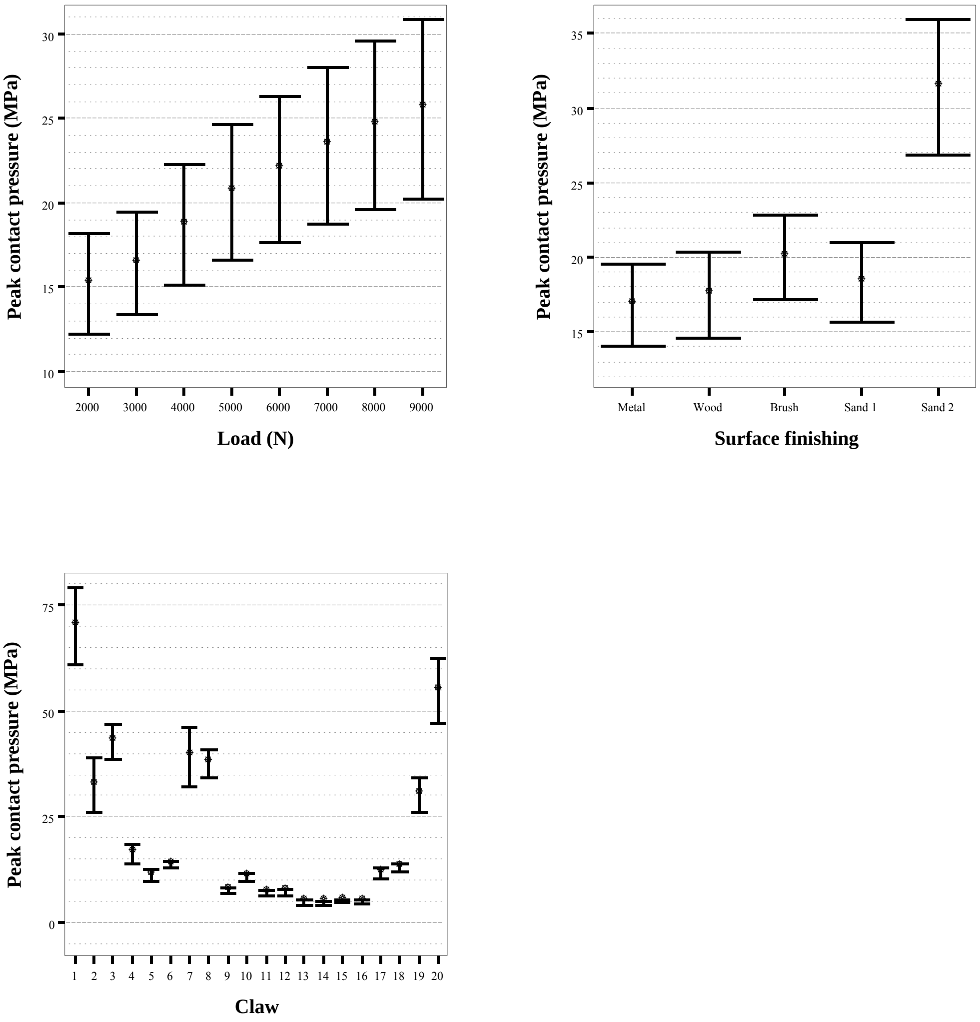

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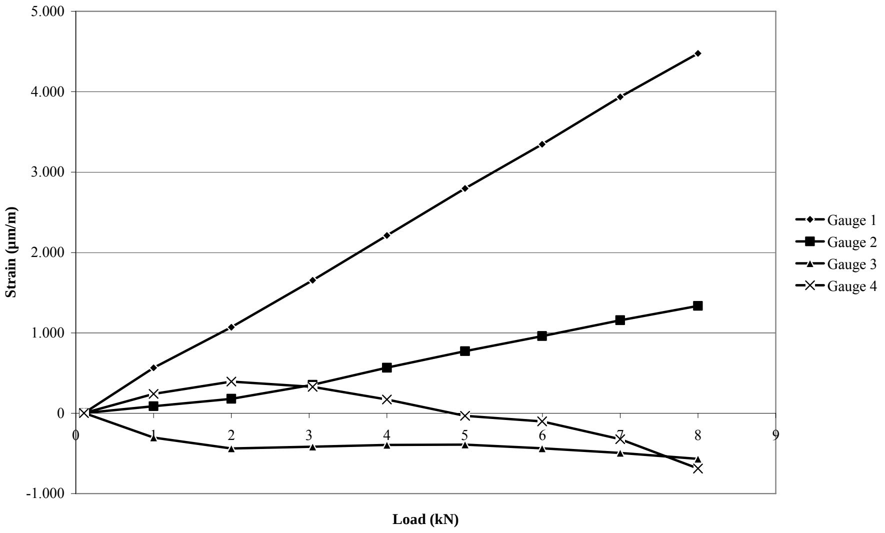

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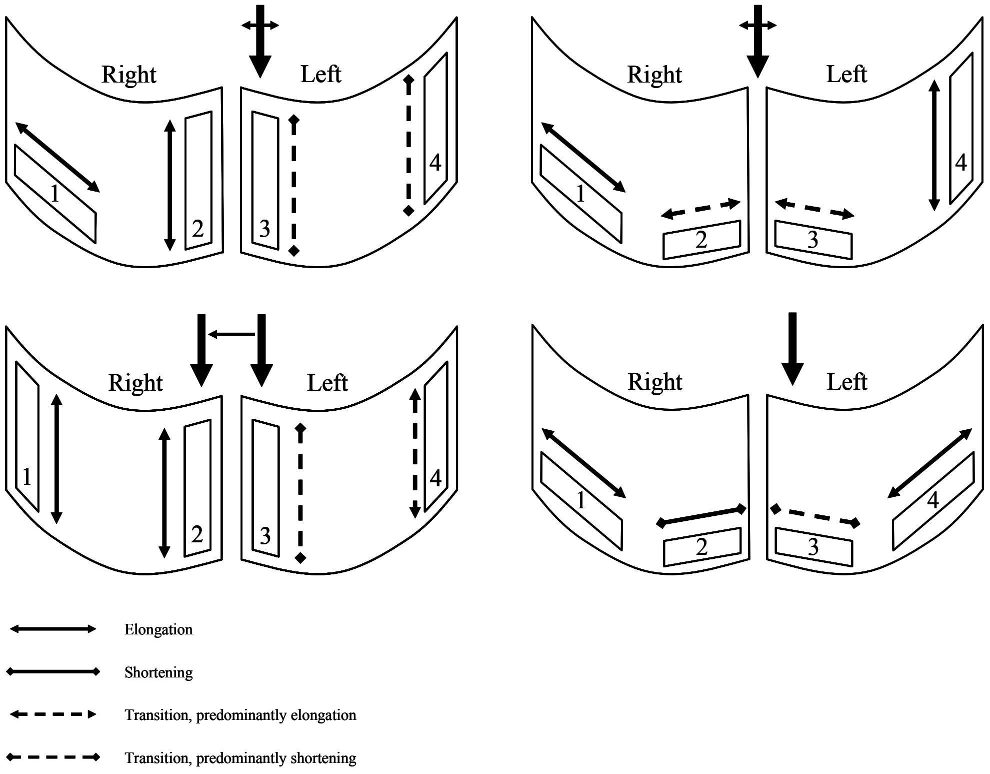

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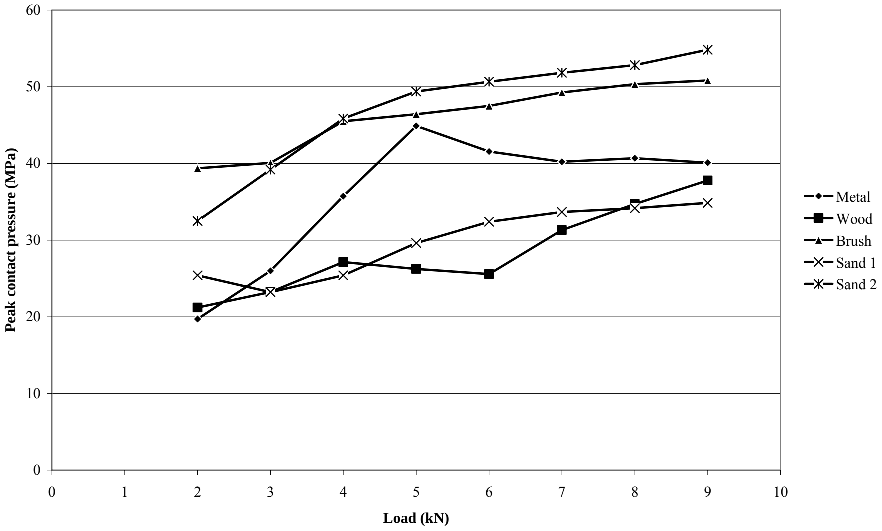

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