Effect of Different Flooring Systems on Weight and Pressure Distribution on Claws of Dairy Cows

E. Telezhenko,*¹ C. Bergsten,*[†] M. Magnusson,‡ M. Ventorp,‡ and C. Nilsson‡

*Department of Animal Environment and Health, Swedish University of Agricultural Sciences, Skara, Sweden

†Swedish Dairy Association, Box 234, 532 23 Skara, Sweden

‡Department of Agricultural Biosystems and Technology, Swedish University of Agricultural Sciences, Alnarp, Sweden

ABSTRACT

Weight and pressure distribution on the claw were studied in Swedish Holsteins housed in different flooring systems. A total of 127 cows housed in different sections of the experimental barn were used. Each section had different flooring in the walking and standing areas. There were rubber mats or abrasive mastic asphalt flooring on the alleys or a low-abrasive slatted concrete floor. Some sections had feed-stalls equipped with rubber mats; other sections did not. The vertical ground reaction force, contact area, and average contact pressure were determined on the left hind foot using the I-Scan system and analyzed with the F-scan system. These determinations were made in each of the following 3 zones of the claw: bulb, wall, and sole. Most of the weight on claws exposed to concrete floors was carried by the bulb (37.4 ± 3.5 and $18.3 \pm 2.9\%$ of weight exerted on the foot in the lateral and medial claw, respectively) and the wall zone (20.0 ± 2.6 and $13.4 \pm 2.4\%$ on lateral and medial claw, respectively). The weight and pressure distribution in cows kept on sections with rubber covered alleys but passing daily over the asphalt floor on their way to the milking parlor did not differ in any zones, except for lateral bulbs, compared with those exposed to slatted concrete alone. Still, the weight bearing of the sole zone in cows kept on rubber mats without access to asphalt was less than that of cows kept on concrete slatted floors (5.1 ± 0.7 vs. $12.7 \pm 1.1\%$ and 1.1 ± 0.5 vs. $8.7 \pm 0.7\%$ in lateral and medial claws, respectively). In cows kept on asphalt flooring without feed-stalls, most weight was exerted to the sole zone (36.2 ± 2.9 and $22.2 \pm 1.8\%$ in lateral and medial claws, respectively). Feed-stalls in combination with asphalt flooring yielded a decreased total contact area ($30.1 \pm 1.2 \text{ cm}^2$) compared with asphalt floors without feed-stalls ($35.7 \pm 1.2 \text{ cm}^2$). The largest total contact area was obtained on the asphalt floor without feed-

stalls, resulting in a lower contact pressure ($39.8 \pm 2.3 \text{ N/cm}^2$) than in claws exposed to concrete ($66.0 \pm 2.7 \text{ N/cm}^2$) or rubber mats ($56.7 \pm 1.7 \text{ N/cm}^2$). In conclusion, housing with abrasive floors resulted in claws with increased contact area at the sole surface and therefore, decreased contact pressure, but reduced the weight-bearing role of the strongest part of the claw capsule, the claw wall.

Key words: dairy cattle, floor, biomechanics, claw

INTRODUCTION

Loose housing, and in particular free-stall systems, for dairy cows is a cost-efficient system which facilitates several animal needs (e.g., free movement and performance of social behavior). Nevertheless, lameness problems impair the functionality of the system because animals with reduced ability to move have difficulty obtaining food and water and accessing the milking facilities, especially in voluntary milking systems. Moreover, lameness is most often a sign of pain and of considerable concern for animal welfare (Bergsten, 2001). The most important part of dairy housing relating to lameness control is the floor surface because of its contact with feet (Webb and Nilsson, 1983; Sommers, 2004).

Designing a proper flooring system is a challenge in free-stall barns. The construction should be durable, hygienic, and reasonably priced. Because the floor is intensively used by heavy animals, there is a great demand on flooring design. Good slip resistance, ease of cleaning, encouraging locomotion, and promotion of claw health are characteristics of an appropriate flooring system, which could be described by a general term, floor ergonomics.

Concrete, which is the most common material used in free-stall barn alleys, was usually characterized as being too slippery for normal locomotion (Webb and Nilsson, 1983; Faull et al., 1996). Both roughness and softness of the walking surface had a positive effect on cow locomotion (Telezhenko and Bergsten, 2005; Ruschen and de Passillé, 2006). Yet, if the surface was too

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¹Corresponding author: Evgenij.Telezhenko@hnh.sl.se

abrasive it caused extreme wear of the claw horn, resulting in thin soles and a greater risk of bruising the sole of the claw (Bergsten, 2001) and penetration by infection resulting in irreparable injuries. The inadequate surface of a concrete floor was improved by resilient coverings such as rubber mats (Benz, 2002), but smooth flooring may cause a reduction in claw wear resulting in increased claw overgrowth (Platz et al., 2007).

The bovine claw protects the distal phalanx from environmental challenges and transfers body-generated forces to the ground. Different parts of the claw serve this function of force transfer: claw wall, suspensory apparatus of the digit, and the digital and coronary cushions (Mülling and Greenough, 2006). The suspensory apparatus, which consists of a system of dense collagenous fibers extending between the pedal bone and the epidermal lamellae of the claw wall, is somewhat less extensive at the axial part of the claw capsule, and is absent posterior to the insertion of the deep flexor tendon and in the region of the digital cushion. Consequently, stretching of the suspension apparatus fibers allows a slight displacement and rotation of the pedal bone, which is part of the shock-absorbing mechanism, but increases the risk of sole hemorrhages and sole ulcers (Lischer et al., 2002). However, the corium of the axial part of sole bulb junction is usually protected by the natural concavity of the sole (Tranter and Morris, 1992). The greatest part of the digital cushion is situated posterior to the navicular bone and seems to play the main role in shock absorption during the first contact of the claw with the ground during locomotion. It was suggested that the bulk of the digital cushion is not weight bearing under static conditions (Mülling and Greenough, 2006).

To improve weight distribution between and within the claws that have been altered by inadequate flooring and by claw overgrowth, functional claw trimming is usually recommended. Functional claw trimming is aimed at achieving equal weight distribution between and within the claws. A larger contact area is considered a desirable effect of the claw trimming. Yet, restoration of the natural slope in the axial part of the claw was recommended (Toussaint Raven, 1989).

Floorings or flooring combinations that can provide a balance between wear and growth of claw horn (Vermunt and Greenough, 1995) may decrease the need for claw trimming. The long-term effect of different flooring systems on claw characteristics, related to its biomechanics, should be scrutinized to provide information about the most favorable flooring for normal function of the claw.

The environmental effects on the conformation of the weight-bearing surface of the claw were investigated

in grazing cows by Tranter and Morris (1992). van der Tol et al. (2004) and Carvalho et al. (2005) investigated the effect of claw trimming on claw pressure distribution. Additionally, Franck and De Belie (2006) described the contact pressure between a bovine claw specimen and floors with different degrees of roughness. Nonetheless, no study described the long-term effect of different flooring surfaces in walking areas on between- and within-claw weight and pressure distribution.

The aim of this study was to investigate long-term effects of different flooring systems providing different roughness and softness on the weight distribution, contact area, and contact pressure in claws of dairy cows in a free-stall system.

MATERIALS AND METHODS

Study Herd

The study took part in an experimental, university dairy herd in the southern part of Sweden (Swedish University of Agricultural Sciences, Alnarp). Average milk production was 9,000 kg of ECM and the culling rate during the 2-yr study period was about 40%, of which low fertility, mastitis, and lameness contributed 12, 6, and 1%, respectively. Lactating cows were housed in a free-stall barn with 200 stalls (1.23 × 2.42 m) in a 2 × 2 row design on both sides of a common, drive-through feeding platform. The concrete free-stall base was covered with a 30-mm-thick polymeric mat (ethyl vinyl acetate, DeLaval Cow Mat CM30L, Tumba, Sweden) bedded with 3.5 to 7 kg of sawdust provided twice weekly.

Five free-stall sections were used in the study. Each section had 21 free-stalls and 1 automatic concentrate feeding station along the outer wall. The alleys between the free-stalls were 2.20 m wide. In 2 sections, along the feeding platform, there were 20 feed-stalls (0.80 × 1.60 m) equipped with hard rubber mats (UBO, Barneveld, the Netherlands). The alley behind the feed-stalls was 2.30 m wide. In the sections without feed-stalls there were 23 head gates per section (0.70 m per head gate) and the total alley width was 3.02 m.

The cows were milked twice daily in a 2 × 9 herringbone parlor equipped with an automatic cluster detaching device. The holding pen (6 × 12 m, ~72 m²) had solid concrete flooring that was designed to accommodate up to 50 cows. The pen was equipped with a mechanical crowding gate. The 30-m connection alley from the free-stalls to the holding pen had slatted concrete flooring. The 4-mo grazing period that is mandatory in this Swedish region started at the beginning of May and ended at the beginning of September.

Floors and Floor Tests

The floors tested included acid-resistant mastic asphalt (BINAB, NCC Roads AB, Stockholm, Sweden), solid (**KURA-P**) and slatted (**KURA-S**) rubber mats (Gummiwerk Kraiburg Elastik GmbH, Tittmoning, Germany), and a slatted concrete floor.

The mastic asphalt (polymer bitumen mixed with siliceous ballast) had a "floated" surface finished with fine rounded sand (maximum particle size of 0.5 mm). The KURA-P mats were joined by jigsaw connections and were screwed to the underlying surface. The KURA-S rubber mats had perforated slots (270 × 40 mm) with a void ratio of approximately 20%, but were otherwise identical to the KURA-P mats. The slatted flooring was made of 125-mm-wide, single, prestressed concrete beams separated with 40-mm-wide plastic profiles (floor void ratio of 24%).

Floor friction assessments were made with a test device designed at the Department of Agricultural Biosystems and Technology (Swedish University of Agricultural Sciences). The device worked according to the drag method. To get reliable values, a synthetic material with constant properties was used as a test body. Beer (1976) found that polypropylene showed very similar coefficients of friction to real claws. A test body used in our experiment made of polyethylene had a hardness of 95° Shore A, which is comparable to results for the claw wall obtained by Sommers (2004). The test body in the shape of a claw was loaded with a 211.5-kg (2,074.8 N) weight, and was pulled horizontally along the floor by a hydraulic piston. The force required to pull the body along the floor was recorded by a load cell placed between the test body and the piston. The ratio between the pulling force and total vertical (normal) force on the test body was calculated by expressing the coefficient of friction. The tests were carried out on flooring in the presence of some superficial slurry (lubricant). Dynamic friction coefficients were used to describe floor friction characteristics, because they are recognized to be superior to describing slip resistance (Leclercq, 1999). For each floor type the test was repeated 9 to 18 times.

The method of dragging a test body (block of plaster, total weight 2,240 g) over a clean and dry flooring surface was applied (Nilsson, 1988) to test the abrasiveness of the floor surface. The degree of abrasion could be determined by weighing the block before and after the drag test. Three measurements were made on each floor type.

The mastic asphalt dynamic coefficient of friction was 0.37 ± 0.002 (mean $\pm$ SD), and the abrasion rate was $4.48 \pm 0.22 \text{ kgm}^{-1} \cdot 10^{-4}$. The average dynamic coefficient of friction measured on rubber mats was 0.53 ± 0.02 ,

and the abrasion rate was $0.32 \pm 0.13 \text{ kgm}^{-1} \cdot 10^{-4}$. The average dynamic coefficient of friction of beams on the slatted concrete floor was 0.29 ± 0.01 , and the abrasion rate was $1.68 \pm 0.12 \text{ kgm}^{-1} \cdot 10^{-4}$.

Animals and Flooring Systems

The 178 Swedish Holstein were used in the flooring studies during 2 consecutive stall periods (September and May). Cows with similar calving dates were introduced into different flooring systems. Because estrus was not synchronized, it took approximately 4 mo to fill groups. At each introduction, cows in even groups were stratified by parity (primiparous and multiparous animals) and randomly assigned (by lottery) to respective flooring systems. Before entering the experimental group (after or just before calving) the claws of all the cows were trimmed using same technique including restoring the slope of the sole (Toussaint Raven, 1989). Not all animals were used in the subsequent analysis of pressure and weight distribution. The reasons for the data exclusions were abnormal claw shape (e.g., corkscrew claw), damaged pressure sensor, and unsatisfactory quality of raw data.

Experiment 1. The cows were allotted in the following flooring systems for 189 d (range: 76 to 249): solid rubber mats (KURA-P; $n = 16$); solid mastic asphalt ($n = 16$); solid rubber mats (KURA-P) with feed-stalls ($n = 15$); solid mastic asphalt with feed-stalls ($n = 17$); and slatted concrete floor ($n = 13$).

All of the solid floors were equipped with fully automatic hydraulic manure scrapers with rubber blades (Delta Master DM II, DeLaval, Tumba, Sweden). The average number of parities was 1.9 (range: 1 to 7). The cows from the sections with rubber mats had to cross the section with mastic asphalt floor on the way to the milking parlor.

Experiment 2. In experiment 2, cows were assigned to the following flooring systems: slatted rubber mats (KURA-S) with scrapers; $n = 16$); slatted rubber mats (KURA-S) without scrapers; $n = 17$); and concrete slatted floor ($n = 17$).

In contrast to experiment 1, cows in the section with rubber mats did not cross the mastic asphalt floor. Average number of parities was 2.02 (range: 1 to 6). The cows were kept in respective flooring systems for 172 d (range: 134 to 213). All management routines and other housing conditions were similar to those in experiment 1.

Pressure Plate Measurements and Data Processing

Measurement System. The measurements were performed with an I-Scan system (Tekscan Inc., Boston,

MA), which was a complete system including both hardware and software components. The pressure sensor (5250 CMP, Tekscan Inc.) is an ultrathin (0.10 mm) flexible printed circuit with a 246- × 246-mm measuring surface and 3.202 sensing elements (sencells) per cm². The sensor measured the vertical force only. Calibration was performed to convert the raw digital output to the actual measurement of force (N). The pressure sensor was calibrated with a hydraulic press equipped with a load cell (LPM-1-PI, Bofors, maximum loading 200 kN, error 0.76%) according to the manufacturer's procedures (Tekscan Inc.). During the measurements the sensor was placed on a specially made stainless steel plate (1.5 mm thick) and was covered first with a 0.12-mm-thick polytetrafluoroethylene (02-QSP12, Fluorweb AB, Åkersberga, Sweden) dipped glass-fiber fabric (to prevent noise from horizontally directed forces) and then covered with a 1-mm-thick rubber cloth in experiment 1, or with a 5-mm rubber cloth in experiment 2 (to protect the sensor and prevent the claw from slipping).

Measurement Procedure and Analysis. The measurements were carried out in April and May in the respective experiments before claws were trimmed. Before the measurements the claws were cleaned and a digital photograph of the claw sole was taken (Bergsten, 1993). A size reference was placed at the claw sole level to permit matching of the sole images later with sensor images. The cows were positioned in a hydraulic trimming chute with the left hind foot on the pressure plate. Recording was performed when the cow was standing in a steady position and supported by all 4 feet. During the measurements, special attention was paid to prevent the cow from leaning on the chute. Three measurements were performed per cow, where each measurement included 500 frames (1,500 frames per cow in total) with a frequency of 100 frames/s.

Analysis of data was with the F-scan system (Research TAM Version 5.22, Tekscan Inc., Boston, MA), which was compatible with the I-scan output. The F-scan system was similar to I-scan, but had a wider possibility for subsequent analysis with flexible determination of different zones of the color-coded output. Each measurement (500 frames) was averaged to a single image, which was subjected to subsequent analysis.

Each claw sole (lateral and medial) was divided into 3 zones: bulb, wall, and sole (Figure 1). To define the zone on the color-coded outputs, they were individually matched with the digital photographs of the corresponding claw sole. The border between the sole and the bulb zones was determined with reference to the posterior wall zone; that is, the line dividing sole and bulb zones that begins perpendicular to the posterior end of the white line of the abaxial wall. The 3 zones for each claw

Figure 1. Claw zones used in evaluation of vertical ground reaction force, contact area, and contact pressure.

were marked (polygon function, F-scan, Tekscan Inc.) individually for each of the averaged frames. Only color-coded outputs with appropriate resolution of different zones (i.e., that could be reasonably well matched to the digital images of the soles of the claws) were used for analyses. The vertical ground reaction force (GRF), contact area, and average pressure were determined within the defined zones for each claw. To account for the partial contribution to the contact area of sensors located at the edge of the claw contact area, the threshold level was experimentally set to 8 and 15 N per sencell for experiments 1 and 2, respectively. The contact pressure was obtained by dividing the actual vertical force by the corrected contact area.

Statistical Analysis

The statistical analysis was made using ANOVA with a mixed linear model (PROC MIXED procedure in SAS 8.02; SAS Inst., Cary, NC). The preliminary analysis found no differences between cows in the sections with rubber mats with or without feed-stalls (experiment 1) and with or without scrapers (experiment 2). Therefore, all animals in sections with rubber mats within each experiment were combined into 1 group (rubber mats) for the statistical analysis. The results of the 2 experiments were analyzed separately, but using a similar model. Lactation number was categorized in 3 groups: first lactation (experiment 1, n = 39; experiment 2, n = 19), second lactation (experiment 1, n = 19; experiment 2, n = 18), and third and greater lactations (experiment 1, n = 19; experiment 2, n = 13). The number of days the cows spent in each particular flooring system after claw trimming was categorized into 3 groups: <150 d (experiment 1, n = 15; experiment 2, n = 15), 150 to

Table 1. Comparisons of vertical ground reaction force distribution (% of total vertical ground reaction force exerted to the foot) on weight-bearing surface of the left hind foot of cows kept in different flooring systems in experiment 1

Claw zones	Slatted concrete		Rubber mats		Asphalt with feed-stalls		Asphalt without feed-stalls	
	LSM	SE	LSM	SE	LSM	SE	LSM	SE
Lateral claw	65.0 ^a	4.3	57.9 ^a	2.7	59.4 ^a	3.6	56.1 ^a	3.7
Bulb	37.4 ^a	3.5	24.5 ^b	2.2	16.4 ^{bc}	2.9	12.4 ^c	2.9
Wall	20.0 ^a	2.6	20.7 ^a	1.6	9.3 ^b	2.1	7.5 ^b	2.2
Sole	7.6 ^b	3.4	12.7 ^b	2.2	33.7 ^a	2.9	36.2 ^a	2.9
Medial claw	35.0 ^a	4.3	42.1 ^a	2.7	40.6 ^a	3.6	43.9 ^a	3.7
Bulb	18.3 ^{ab}	2.9	19.1 ^a	1.8	11.8 ^{ab}	2.4	9.1 ^b	2.4
Wall	13.5 ^a	2.4	16.7 ^a	1.5	10.9 ^a	1.9	12.5 ^a	2.0
Sole	3.2 ^a	2.1	6.3 ^a	1.3	17.9 ^b	1.8	22.3 ^b	1.8

^{a-c}Least squares means (LSM) within a row with different superscripts differ ($P < 0.05$).

200 d (experiment 1, $n = 31$; experiment 2, $n = 27$) and >200 d (experiment 1, $n = 31$; experiment 2, $n = 8$). The final model for analysis of force and pressure data included flooring system and lactation number, and categorized days in the study as fixed factors and cow as repeated and random factor nested within the flooring system, lactation number, and days in study.

Because the weight of animals was unknown, and because it was impossible to determine which proportion of their own weight that was put on the limb at a given moment, the vertical GRF applied to the different claws and zones was analyzed as the percentage of the total force applied to the foot. A covariate for total vertical GRF applied to the foot was used in the models to describe contact area and contact pressure. Those variables that did not meet assumption of normality were square root transformed. To present the results in the original scale, the back transformation of predicted values was made. A compound-symmetry correlation structure was used for repeated measurements, assuming all observations were equally correlated within cow. The possible 2-way interactions were tested. Least squares means were processed from the models and multiple comparisons were performed with Tukey-Kramer adjustment. A 5% ($P < 0.05$) significance level was used throughout all comparisons.

RESULTS

Experiment 1

The animals exerted $1,423 \pm 28$ N (mean $\pm$ SE) to load their hind left limb. No significant interactions were found between lactation number, floor and days in the study. Contact area of the medial bulb zone was reduced ($P < 0.01$) in older cows (2.1 cm^2) compared with animals with 1 or 2 lactations (3.2 and 3.6 cm^2 , respectively). The contact area of the medial wall zone was reduced ($P < 0.01$) with increasing time after the

claw trimming (4.3 , 4.0 , and 2.8 cm^2 corresponding to the 3 groups of categorized time). The increased time being in the study was associated with decreased vertical GRF ($P < 0.01$) exerted on the medial wall zone (17.0 , 13.8 , and 9.2 N/cm^2 for <150, 150 to 200, and >200 d in study, respectively), but irrespective of the particular flooring system. Analysis of the relative vertical GRF distribution revealed a significant difference within claw weight distribution in cows kept on asphalt floors compared with those on rubber mats and concrete slats (Table 1). Cows from rubber flooring systems had a greater vertical GRF exerted to the lateral wall zone (20.7%) and a lower force exerted to the lateral sole (12.7%) than cows kept on asphalt floors. The sole zone was less loaded in the medial claws in cows kept on rubber (6.3%) and slatted concrete floors (3.2%) than on asphalt ($\sim 20\%$). There were no differences in vertical GRF distribution of the wall of the medial claw in any of the groups. There were no significant differences in the relative vertical GRF distribution between cows from slatted concrete and rubber mats with the exception of the lateral bulb area, where cows from concrete slats (37.4%) had the greatest weight applied. None of the flooring systems differed significantly in relative weight distribution on the whole medial or lateral claw.

Cows kept on asphalt floors without feed-stalls had the largest total contact area (Table 2). The increased contact area was almost entirely a product of significantly increased contact area in the sole zone. The contact areas of the other zones in cows on asphalt flooring without feed-stalls were similar to the other groups or even smaller. The contact area of the lateral sole zone in cows kept on asphalt floor with feed-stalls (9.7 cm^2) was numerically smaller than without feed-stalls (12.9 cm^2), but still significantly larger than on the rubber mats (4.5 cm^2) and on the slatted concrete floors (2.2 cm^2).

Cows confined on slatted concrete floors had a significantly greater average contact pressure exerted to

Table 2. Comparisons of contact area (cm²) of the weight-bearing surface of the left hind foot of cows kept in different flooring systems in experiment 1

Claw zones	Slatted concrete		Rubber mats		Asphalt with feed-stalls		Asphalt without feed-stalls	
	LSM	SE	LSM	SE	LSM	SE	LSM	SE
Lateral claw	14.4 ^b	1.2	15.8 ^b	0.8	18.2 ^{ab}	1.1	21.00 ^a	1.1
Bulb	6.8 ^a	0.8	6.4 ^a	0.5	5.3 ^a	0.7	4.9 ^a	0.7
Wall	5.3 ^a	0.5	4.9 ^a	0.3	3.2 ^b	0.4	3.2 ^b	0.4
Sole	2.2 ^b	1.1	4.5 ^b	0.7	9.7 ^a	0.9	12.9 ^a	0.9
Medial claw	7.4 ^c	0.91	9.7 ^{bc}	0.6	11.7 ^b	0.8	14.7 ^a	0.8
Bulb	3.1 ^a	0.4	3.4 ^a	0.2	2.7 ^a	0.3	2.7 ^a	0.3
Wall	3.4 ^a	0.4	4.2 ^a	0.3	3.6 ^a	0.4	3.8 ^a	0.4
Sole	0.9 ^c	0.6	2.0 ^c	0.4	5.4 ^b	0.5	8.1 ^a	0.6
Foot total	21.8 ^c	1.4	25.5 ^c	0.9	30.1 ^b	1.2	35.7 ^a	1.2

^{a-c}Least squares means (LSM) within a row with different superscripts differ ($P < 0.05$).

the lateral claw (64.8 N/cm²) than the animals in all the other flooring systems (Table 3). The average contact pressure applied to the bulb (57.9 N/cm²) and wall (60.5 N/cm²) zone in cows kept on rubber mats was significantly greater than in cows on asphalt flooring without feed-stalls (32 and 33.7 N/cm², respectively). There were fewer differences in the average contact pressure of the medial claw; only the bulb area of cows kept on concrete (74 N/cm²) and rubber (77.4 N/cm²) had a greater pressure than cows on asphalt floors without feed-stalls (43.2 N/cm²).

Experiment 2

The cows exerted $1,643 \pm 28$ (mean $\pm$ SE) N to load their hind left limb. Similar to results of experiment 1, the contact area of the medial bulb zone was reduced ($P < 0.05$) in older cows (2.2 cm²) compared with animals with 1 or 2 lactations (3.1 and 3.4 cm², respectively). The older cows exerted less pressure ($P < 0.01$) on the medial bulb zone (62.2 N/cm²) and on the entire medial claw (64.8 N/cm²; $P < 0.01$) than did primiparous cows (99.0 and 78.2 N/cm² for medial bulb and medial claw,

respectively). No significant interactions were found among lactation number, floor, and days in the study.

When comparing measurements obtained from cows on rubber mats (without any contact with asphalt flooring) with their herd mates on concrete slatted floors there was a significantly greater value of vertical GRF (34.2 vs. 25.9%) applied to the bulb area in claws of cows kept on the rubber flooring (Table 4). Significantly more force was applied on both lateral (12.7 vs. 5.1%) and medial (8.1 vs. 1.1%) sole zones when the animals had concrete alleys. The contact area of the sole zone was significantly smaller after exposure to rubber flooring both for lateral (3.9 vs. 1.5 cm²) and medial (2.2 vs. 0.5 cm²) claws (Table 4). The average contact pressure did not differ between the experiment groups with exception of the pressure within the sole zone of the lateral claw, which was smaller (50.8 vs. 35.1 N/cm²) in the group on rubber mats (Table 4).

The color-coded output of the I-Scan, matched with the respective claw images of cows kept in different flooring systems, is presented in Figure 2. A color version of this figure is available online (<http://jds.fass.org/content/vol91/issue5/>).

Table 3. Comparisons of average contact pressure (N/cm²) distribution on weight-bearing surface of the left hind foot of cows kept in different flooring systems in experiment 1

Claw zones	Slatted concrete		Rubber mats		Asphalt with feed-stalls		Asphalt without feed-stalls	
	LSM	SE	LSM	SE	LSM	SE	LSM	SE
Lateral claw	64.8 ^a	3.7	52.5 ^b	2.3	49.7 ^{bc}	3.1	36.7 ^c	3.2
Bulb	76.7 ^a	3.6	57.9 ^b	2.2	40.5 ^c	3.1	32.0 ^c	3.1
Wall	50.9 ^{ab}	7.3	60.5 ^a	4.5	41.7 ^{ab}	6.1	33.7 ^b	6.2
Sole	41.7 ^a	5.8	40.3 ^a	3.7	52.3 ^a	4.9	38.7 ^a	5.0
Medial claw	63.4 ^a	4.7	60.7 ^a	2.9	48.2 ^{ab}	4.0	43.1 ^b	4.1
Bulb	74.0 ^a	8.7	77.4 ^a	5.5	56.2 ^{ab}	7.4	43.2 ^b	7.5
Wall	53.6 ^a	5.3	54.3 ^a	3.3	40.3 ^a	4.5	41.8 ^a	4.5
Sole	30.3 ^a	5.9	33.5 ^a	3.7	45.9 ^a	5.1	40.2 ^a	5.1
Foot average	66.0 ^a	2.7	56.7 ^b	1.7	47.8 ^c	2.3	39.8 ^c	2.3

^{a-c}Least squares means (LSM) within a row with different superscripts differ ($P < 0.05$).

Table 4. Comparisons of measures of the weight-bearing surface of left hind foot of cows kept in different flooring systems in experiment 2¹

Claw zones	Vertical ground reaction force (% of total)				Contact area (cm ²)				Average contact pressure (N/cm ²)			
	Slatted concrete		Slatted rubber		Slatted concrete		Slatted rubber		Slatted concrete		Slatted rubber	
	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
Lateral claw	59.8 ^{NS}	4.0	66.7	2.7	14.4 ^{NS}	0.9	15.1	0.7	66.5 ^{NS}	4.8	74.0	3.6
Bulb	25.9*	2.9	34.2	2.0	5.2**	0.4	6.7	0.3	79.0 ^{NS}	6.2	85.0	4.6
Wall	20.8 ^{NS}	3.0	27.2	2.1	5.1 ^{NS}	0.6	6.3	0.4	55.9 ^{NS}	5.9	64.1	4.4
Sole	12.7**	1.1	5.1	1.4	3.9**	0.5	1.5	0.4	50.8*	7.0	35.1	5.2
Medial claw	40.2 ^{NS}	4.0	33.3	2.7	9.1 ^{NS}	0.6	7.9	0.5	67.8 ^{NS}	4.1	68.9	3.0
Bulb	15.3 ^{NS}	2.4	15.4	1.6	2.7 ^{NS}	0.3	2.9	0.2	81.5 ^{NS}	8.8	77.5	6.4
Wall	16.1 ^{NS}	1.9	16.9	1.3	4.1 ^{NS}	0.4	4.5	0.3	59.4 ^{NS}	4.9	60.5	3.2
Sole	8.1***	0.7	1.1	0.5	2.2**	0.3	0.5	0.2	44.6 ^{NS}	5.8	38.3	4.3
Foot	—	—	—	—	23.7 ^{NS}	0.8	22.9	0.6	70.1 ^{NS}	3.5	73.8	2.6

¹Least squares means (LSM) from the groups on slatted concrete differed from those on rubber at * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; and NS = $P > 0.05$.

DISCUSSION

Effect of Floor

The vertical GRF, contact area, and average pressure distribution within a claw were significantly affected by the different flooring systems studied.

The increase in roughness of floor surface was the main source of the high friction on the hard floor and high abrasion of the claw horn (Bonser et al., 2003). The choice of the asphalt floor was motivated by its relatively constant roughness, which may be compared with freshly cast concrete floor. Yielding rubber mats may increase grip without being abrasive. The tested floorings can be generally categorized according to their properties as being hard (asphalt and concrete) or soft (rubber), with a low (concrete) or a high (asphalt and rubber) coefficient of friction, and with low (rubber, concrete) or high (asphalt) degree of abrasiveness. Most differences in contact area, average contact pressure, and vertical GRF distribution were demonstrated in claws exposed to asphalt in contrast to claws exposed to all the other floorings. From these findings we conclude that abrasiveness had the greatest influence on the studied parameters of the claw.

Similar to results by van der Tol et al. (2002), the bulbar region of the hind claws was subject to the greatest stress in claws exposed to concrete and rubber floors. The highly abrasive asphalt flooring gave a different picture of weight distribution compared with low abrasive flooring surfaces. The more abrasive floor (asphalt) increased the total contact area, and the increase was mainly because of increased contact with the sole zone while the contact area of the bulb was similar and the wall zone area was significantly decreased compared with the less abrasive flooring. These changes resulted in a reduced weight-bearing role of the claw walls and to some extent of the bulbs. On the other hand, the

enlarged contact area resulted in a smaller average pressure exerted to the claws. In contrast, results obtained from floors with low abrasion (rubber mats and aged concrete) demonstrated a smaller contact area involving mainly the bulb and wall zones, which resulted in greater average contact pressure exerted to the claws. This supports the findings of Hubert (1993) who showed that cows from free-stalls had a significantly greater contact area and a lower average pressure in their front claws compared with cows kept on a less abrasive surface in tie stalls.

Within a normal claw, forces generated from the body are basically mediated to the ground by the shock-absorbing apparatus (bulbar segment and some elements of sole segment) and the tension forces-transforming area of suspensory apparatus, which corresponds in the strictest sense to the wall segment of the claw (Mülling and Greenough, 2006). Modifications in the conformation of the claw will change its biomechanical characteristics and the above-mentioned functions may be altered, resulting in claw lesions such as sole ulcer and sole hemorrhages. Lischer et al. (2002) found that the shock-absorbing apparatus (digital cushion) was considerably reduced in size in cattle affected with a sole ulcer. Grazing cattle acquire a concave-shaped sole (Tranter and Morris, 1992), where the axial inclination of the sole leaves the claw wall margin and the bulbar part in contact with the hard smooth surface. In the present study, before animals were introduced to their respective flooring systems, a certain sole concavity was created by dishing the axial part of the sole at claw trimming (Toussaint Raven, 1989). Nonetheless, a greater proportion of the sole zone increased the contact area with the flat surface of the pressure plate after exposure to asphalt floors, which is in accordance with the results of Tranter and Morris (1992), who demonstrated a rapid decrease in the initial concavity after

Figure 2. Results of color-coded output of I-Scan (Tekscan Inc.) matched with claw images in Swedish Holstein cows kept in different flooring systems: a) low abrasive concrete slatted floor; b) rubber mats (KURA-S); c) mastic asphalt floor with feed-stalls; d) mastic asphalt floor without feed-stalls. Color figure is available online (<http://jds.fass.org/content/vol91/issue5/>).

repeated contact with rough surfaces of gravel tracks and concrete yards.

Lack of sole concavity was associated with increased risk of lameness (Tranter et al., 1993). Furthermore, the large contact area of the sole caused by rough flooring may not result in a pressure as low as on the very flat and smooth test surface (pressure plate) compared with when the claw was placed on a rough floor (Franck and De Belie, 2006). Therefore, we suggest that long-term exposure to abrasive asphalt floors, which reduces the force-transferring function of claw walls and in some extent the bulbs, potentially increases the risk for injuries to the corium of the sole.

The mechanical stress from rough flooring will not necessarily have adverse effects on claws. Limited exposure to hard and abrasive surfaces can control claw overgrowth (Webb and Nilsson, 1983). In cows housed on rubber mats without daily access to the abrasive flooring (experiment 2), a considerable amount of

weight was carried by the lateral bulb. The shift of weight bearing toward the posterior part of the claw on the hard surface was presumably caused by claw horn overgrowth due to low abrasiveness of the rubber mats. Although the loading pattern may be different on the soft floor, on the hard surface (e.g., when the cows walked to the milking parlor) the overburdening of the hind part of the claw may cause contusion of the corium (Bergsten, 2001).

Because of a confounding effect of year and some differences in the measurement routines, we could not directly compare the effect of access to asphalt when animals had rubber alleys. But claws of cows on rubber mats with access to asphalt floor apparently had a greater proportion of the sole zone in contact with the sensor surface than had claws of cows kept on rubber mats without exposure to the asphalt floor. Hence, even short exposure to a rough floor may have an influence on the contact area and therefore, on the distribution

of the vertical GRF within a claw. On the other hand, rubber-equipped feed-stalls reduced the access to abrasive asphalt floors. In this case, feed-stalls in combination with abrasive flooring resulted in a smaller contact area of the sole zone than in animals kept on asphalt without feed-stalls, but did not increase the contact with the wall zone and resulted in the apparently greatest pressure transferred to the sole zone. The claw wall is prone to wear in accordance with the finding that wear occurs most rapidly along the abaxial portion of the claw sole (Tranter and Morris, 1992).

There were fewer differences in pressure plate measurements across the different flooring systems when the medial claws were compared. This supports the findings of Tranter and Morris (1992) who observed that the concavity of the hind medial claws was less altered than in the lateral claws. Although the different flooring systems resulted in changes in weight distribution within a claw, the difference between lateral and medial claws remained similar across the different floorings. The described proportion of the weight applied to the untrimmed lateral and medial claw (about 60 to 40%, respectively) was more balanced than that described by van der Tol et al. (2004) under Dutch conditions (20 to 80% for medial and lateral claws, respectively).

Methodological Considerations

Both experiments were performed under a static loading situation with a standing cow, in which the pressure was not as extreme and the distribution of ground reaction forces not as critical as in certain moments of a dynamic situation when the cow is walking (van der Tol et al., 2003). The floor abrasiveness modified the shape of the weight-bearing surface, but claw trimming techniques should be taken into account when comparing results from different studies. This may explain why the distribution of vertical GRF and pressure found in the present study did not completely correspond to the results found by van der Tol et al. (2002, 2004) and Carvalho et al. (2005). In the latter studies, a variant of the Dutch method of claw trimming was applied, in which claw soles were trimmed totally flat to redistribute weight on a larger area. Therefore, the contact area of the claw was greater (van der Tol et al., 2004) and significant pressure was exerted on the axial portion of the claw sole (Carvalho et al., 2005). The trimming technique applied in the present study attempted to restore the natural slope of the axial part of the sole, with the result that most weight was exerted on the bulbar region and the abaxial portion of the weight-bearing border. Obviously, floors with low abrasiveness did not affect the slope of the sole, but the

average pressure exerted on the foot (about 70 N/cm²) was greater than that obtained by van der Tol et al. (2004), whose result for pressure for hind feet was about 50 N/cm².

The results of the present study represented the claw weight and pressure distribution averaged for 5-s periods. The averaging of the series of frames represented a picture of possible contact area during standing, but the contact area may be larger than recorded in each 0.01 s. This can result in lower recorded contact pressure. The results reflected the functional conformation of the claw rather than a description of the real stress applied to the claw. Moreover, the results do not represent the real picture of a claw-floor contact in different flooring systems because the cows were examined on a standardized surface (a metal plate bedded sensor with 1- and 5-mm rubber coverings in experiments 1 and 2, respectively). The rubber cloths were used to protect the sensor. The choice of a thicker rubber cloth in the second experiment was because of a low durability of the 1-mm-thick rubber in the first experiment. The thicker layer between the claw and sensor resulted in larger contact area and lower pressure because of the deformation of the rubber. Therefore, a higher threshold for correction of contact area was used in experiment 2. The results did not present a correct modeling of pressure distribution on a hard, rough floor and particularly on soft flooring. We should presume that a larger contact area exerted less pressure when claws interacted with a yielding floor. Studies of a computer-based finite element model of a bovine claw showed that a softer surface allowed a distribution of pressure over a larger area of both claw and floor (Hinterhofer et al., 2005). The application of the results obtained for hard floors had some limitations, because the sensor surface represented a very smooth floor, whereas the actual roughness of the floor affected contact pressure and contact area (De Belie and Rombout, 2003). In addition, a slatted floor may cause a greater mechanical stress as only some parts of the weight-bearing surface may be involved (Hinterhofer et al., 2006a).

A more informative approach (in terms of interaction between the claw and the actual floor surface) for assessing pressure distribution at the claw-floor interface was tested *in vitro* by De Belie and Rombout (2003) and Franck and De Belie (2006), where the sensor was placed directly between the floor and a claw specimen embedded in epoxy resin. Nevertheless, drawbacks from *in vitro* studies were determined by the unnatural arrangement of the artificial foot where lateral and medial claws were solidly attached to an epoxy resin block at the same level. Another drawback of the *in vitro* model was that, while testing pressure distribution on floors with different roughness, the tested claws had

not been exposed to the respective floors previously. As shown in the present study, high abrasiveness of the floor increased claw contact area and affected force and pressure distribution. A direct application of a pressure sensor between the claw and the floor in vivo seems impractical, because there is a high risk that the sensor will be damaged. Development of a more natural in vitro model of the claw is needed in which short-term and long-term effects of tested floorings on claws could be taken into account. Results obtained with a pressure plate may show how much stress is applied on a certain part of the contact area of the claw weight-bearing surface and estimate the risk of horn damage. Because of its limited strength, the bulb horn was most prone to possible damage when high stress was applied (van der Tol et al., 2002; Franck and De Belie, 2006). Both in vivo and in vitro methods will have inherent problems because the pressure distribution of the claw on the pressure plate may not reflect the pressure exerted on the underlying claw tissues. Hollow parts of the sole horn area may act as arches and be a part of weight exertion. Moreover, high contact pressure obtained in the distal part of the claw wall may be quite low in relation to the underlying structures, because it is distributed over the large surface of lamellae. To answer the question about the amount of stress on the underlying structures of the claw, development of more sophisticated techniques is required such as finite element analysis of the bovine digit (Hinterhofer et al., 2006b). However, to date, finite element analysis, representing only a momentary situation, has limited abilities to reproduce the complicated dynamic of the cow foot.

CONCLUSIONS

Intensive exposure to the abrasive flooring (mastic asphalt) caused an increase in contact area and decreased average contact pressure on the claws, which may be considered a positive effect. At the same time, because of the abrasive flooring the role of the most important weight-bearing structure, the claw wall, was significantly reduced. The soft flooring, which combines good friction and low abrasiveness, preserved the claw wall, but exposure to the low-abrasive floors transferred weight distribution toward the bulb region. For that reason, short-term exposure to an abrasive surface can be recommended to provide optimal wear and functional claw shape.

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