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# The Locomotion of Dairy Cows on Floor Surfaces with Different Frictional Properties

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## ABSTRACT

The locomotion of dairy cows was evaluated on floors with a smooth epoxy resin surface or with a surface-applied bauxite aggregate of mean diameter 0.5, 1.2, or 2.5 mm (coefficients of static friction, $\mu$ 0.35, 0.42, 0.49, and 0.74, respectively). Locomotion was recorded as cows walked to receive a food reward. Cows on the floor with least friction walked rapidly (0.85 m/s), with frequent, short steps. At the start of the supporting phase the upper limbs were more vertical. Joint arcs during this phase were reduced. Cows on 0.5-mm aggregate also walked rapidly (0.84 m/s); they had the least vertical limb angles and long steps but held the hoof more vertical, probably to offset any increased slip risk. On floors with larger aggregate, cows decreased speed and step frequency but maintained long steps, keeping their upper forelimbs more vertical to reduce the supporting limb phase. It is concluded that on a low friction floor ($\mu < 0.4$), cows walk quickly with frequent, short steps. As $\mu$ increases to 0.5, step length increases and the number of steps decreases to maintain speed at increased friction, producing an optimal coefficient of friction between 0.4 and 0.5. Further increases in $\mu$ may increase the hanging limb phase at the expense of the supporting limb phase, to reduce friction, while maintaining a long stride to expedite arrival at the reward.
(**Key words:** locomotion, floor, friction, dairy cattle)

**Abbreviation key:** $\mu$ = coefficient of friction.

## INTRODUCTION

The incidence of hoof and leg problems has increased in European cattle in recent years, and now is up to 50% of housed cows in some regions (Distl, 1995). Concrete is used for most passageway floors in cattle buildings because it is relatively durable, impervious to water, and readily available. Its hardness leads to abnormal hoof growth, which may predispose cattle to sole hemorrhage (Bergsten and Frank, 1996). It is usually laid to provide a rough surface after the concrete has cured, which may cause excessive abrasion when cattle are loose-housed (Dirksen, 1997). However, it is rapidly worn smooth by the action of the cows' hooves and tractors passing over it to remove excreta. It then becomes slippery for both the cows and people operating in the building (Schlichtung, 1987), leading to abnormal gait and injury in the cows. In addition, a significant proportion of floors in slaughterhouses are judged to be too slippery, which impedes cattle locomotion (Grandin, 1996). There is little empirical basis for assessment of optimum levels of friction. However, Web and Nilsson reported that the incidence of slip increases rapidly as floors' coefficients of static friction decrease below 0.4 (Webb and Nilsson, 1983). No information is available on the effects of high friction floors on cattle locomotion. Humans walk faster and their gait changes when they are confident that they will not slip (Li, 1999). Having previously observed that cows walk more slowly and have more acute leg angles when a floor is covered with a slurry of excreta, compared with a dry floor (Phillips and Morris, 2000), we measured these variable in cows walking on floors with different levels of friction.

Recently, floors surfaced with aggregate embedded in an epoxy resin matrix have been developed for industrial areas where slip risk has to be minimized, e.g., in factory floors, and in public areas where the surface may become wet and slippery, e.g., around swimming pools. These surfaces are also useful to protect concrete in livestock buildings where it is eroded by acidic excreta (De Belie, 1997). Such floors may be of benefit in cattle buildings at key points where the risk of slip is greatest, e.g., around drinking troughs or at the entrance to the parlor. However, the optimum aggregate size in such a surface is unknown. A very small diameter aggregate is likely to do little to enhance the slip resistance of the epoxy resin matrix in which it is laid, and the smooth surface of the resin offers little slip

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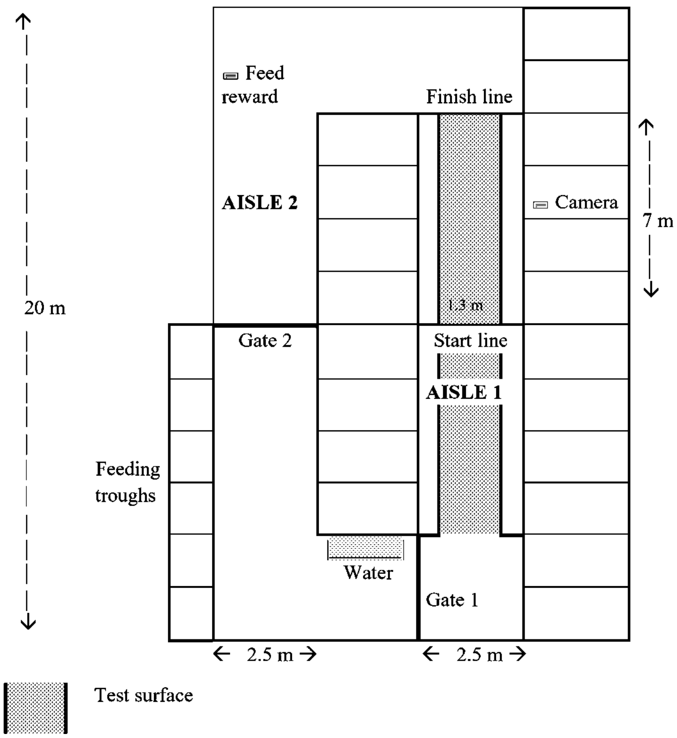


**Figure 1**. Overhead view of the experimental building.

resistance to cattle. However, in floors with larger aggregate, walking may be impaired by excessive friction. Should any large pieces of aggregate become loose and embedded in the cow's hoof, they may cause sole bruising, puncturing of the sole or separate the wall and sole at the white line (zona alba).

An experiment was, therefore, conducted to examine the walking behavior of dairy cows on floors surfaced with epoxy resin and surface-dressed with different-sized aggregates to provide different levels of friction.

## MATERIALS AND METHODS

An experimental building with two 20- × 2.5-m concrete aisles and two rows of 12 free stalls was used for the study (Figure 1). The two aisles were connected at each end of the building by a passageway so that cows could complete a circuit around one of the cubicle rows. At the beginning of the second aisle, a feed trough was placed, in which a feed reward of 120 g of concentrate was offered each time a cow completed a circuit of the building. A gate was placed to restrain each cow before she started walking down the first aisle. The cow therefore walked down the first aisle, along the passageway connecting the two aisles, collected her reward, and returned down the second aisle. Locomotive behavior was recorded in the second half of the first aisle. The positioning of the reward was chosen to ensure that her walking movements at the end of the first aisle were not affected.

Five nonlactating British Friesian cows in their second parity were selected from the University of Wales, Bangor, dairy herd for the study. They were trained to complete the circuit and collect the reward for 9 h prior to the commencement of the study. During the experiment, four floor treatments were laid along the length of the first aisle, which was reduced to a width of 1.3 m to accommodate the floor surfaces. The cows returned to a holding pen at the end of the second aisle during the testing period. They were tested from 1000 h until the second milking at 1500 h each day. At other times they remained with the rest of the herd in another cubicle building, where they were fed a complete diet of 68% grass silage, 22% wheat distillers' grains, 7% molasses, 2% barley, and 0.35% minerals and vitamins, offered ad libitum. The free-stall building was similar in design but larger than the experimental building and the slurry was removed from passageways at each milking.

A switchback design was used for the experiment to ensure that learning did not influence the results. Each cow was tested on three occasions on each surface, each occasion comprised five consecutive circuits for each cow and lasted 1 d. Each cow was therefore recorded 15 times on each surface.

The four surfaces tested were: an epoxy resin with no aggregate and 0.5, 1.2, and 2.5 mm bauxite aggregates embedded in the same epoxy resin matrix (Addaflor, Addagrip Surface Treatments UK Ltd, Uckfield, West Sussex, UK). First, an epoxy resin primer (Addaprime, Addagrip Surface Treatments UK Ltd.) was painted at a rate of 0.28 kg/m$^2$ onto 24 Stirling boards, made from a wood chip and resin composite, to provide six boards per treatment. Each board was 2.3 × 1.3 m, providing 15 m of floor surface by laying the boards end to end in the first aisle. When this had dried the epoxy resin matrix (Addaflor) was painted at the same rate onto the board surfaces. For the aggregate treatments, bauxite of mean diameters 0.5, 1.2, and 2.5 mm was spread evenly as a surface dressing at the recommended rates of 1.5 kg/m$^2$ for the 0.5 and 1.2 mm aggregates and 1.9 kg/m$^2$ for the 2.5-mm aggregate.

### Floor Measurements

The properties of the floor surfaces were characterized by measuring their frictional coefficients and abrasion rate. The coefficients of static and sliding friction were measured with a weighted platform with four hooves beneath it to simulate a cow moving over the floor (Phillips et al., 1998, 1999). Four lower limbs severed at the distal carpus and tarsus joints were obtained from an abattoir and trimmed to approximately 18 cm in length. They were from a cow that was assessed by abattoir staff as having an even gait. The limbs were inserted into four steel cylinders of diameter 105 mm that were attached to the 1 × 0.45 m platform, weighted with 150 kg in barrels of water. Previous research had determined that the force required to move the platform was proportional to its weight and that the frictional coefficients did not vary with different weights (Phillips et al., 1998). A nylon rope connected the platform to a strain gauge via pulleys and the minimum force required to move the platform was recorded three times for each surface. The coefficient of static friction was calculated by dividing this force by the mass of the weighted platform. The coefficient of sliding friction was calculated similarly, but using the minimum force required to maintain movement in the platform. Each coefficient was measured five times at different points of the test aisle.

The abrasion rate of the different surfaces was measured by recording the loss of mass of a carbon rod, which was attached to an electric motor that caused it to scroll in a circular movement (Webb and Nilsson, 1983). The motor was moved down a 2.1-m track over a period of 20 s to prevent accumulated carbon deposits on the floor from affecting the abrasion rate of the rod. This was achieved by attaching the motor to a pulley with nylon rope and using weights attached to the rope to achieve a constant force during the different surface tests. At the end of the test, the rod was removed from the motor and weighed to determine the difference in mass. Ten measurements were made for each of the two surfaces at different points of the aisle.

### Cow Measurements

For this study, the components of cattle stride were divided into three phases—lifting the leg, swinging the leg, and supporting the cow's body mass.

During each cow's transition down the aisle, the number of steps and time taken to complete the latter 7 m of the test aisle was recorded with a stopwatch. A step was defined as the sequence of movements between one lift phase and the next. Step length therefore was the distance covered between two consecutive lift phases of the same limb. A video camera was positioned three-quarters of the way down the first aisle and recorded one support phase of the left fore and hind limbs as they passed. A Panasonic wV-1450/B video camera (Mitsuishita, Uxbridge, Middlesex, UK) and a Hitachi VT-L30ED-UK videorecorder (Hitachi, Hayes, Middlesex) were used. The elbow, carpal, and metacarpophalangeal joints of the forelimb and the stifle, tarsal, and

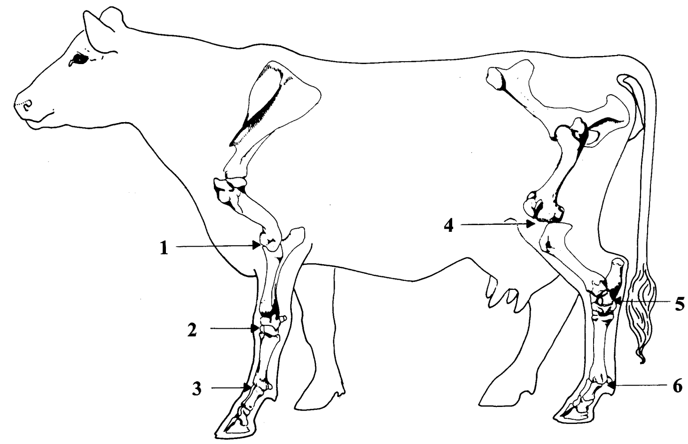


**Figure 2**. Location of the limb joints for which movement was recorded. 1 = elbow; 2 = carpal; 3 = metacarpophalangeal; 4 = stifle; 5 = tarsal; 6 = metatarsophalangeal. (Modified from Figure 9.1 in Blowey, R. W., A Veterinary Book for Dairy Farmers, and reproduced with the permission of Farming Press, Ipswich, U.K.)

metatarsophalangeal joints were each marked with a spot of blue paint at the fulcrum to aid identification of the center point of the joint during subsequent angle measurements (Figure 2). The video recordings were replayed and the angle of each joint at the start, and end of the supporting phase was recorded for all treatments, as well as the angle between the back of the fore and hind feet and the floor (foot angle), which is a reflection of the combined angles of the proximal and distal inter-phalangeal joints.

### Statistical Analysis

The data of cow movement and leg angles were subjected to the Anderson-Darling test and shown to be normally distributed (Ryan et al., 1985). Locomotive data, leg angles, coefficients of friction, and abrasion rates were subjected to analyses of variance using the Minitab statistical package (Ryan et al., 1985). Treatment (nested within replication and circuit), replication, cow, and circuit (nested within replication) were included as factors in a generalized linear model. Significance differences were defined by $P < 0.05$.

## RESULTS

The coefficient of static friction for the No aggregate treatment was low (0.33) and did not differ from the coefficient for sliding friction for this treatment (0.34, Table 1). In the treatments with aggregate, the sliding friction coefficients were greater than static friction. They were similar for the 0.5- and 1.2-mm aggregate and increased for the 2.5-mm aggregate. The abrasion

**Table 1**. The coefficients of static and sliding friction of four hooves and the brasion rate of a carbon rod on the floor surfaces with no aggregate or with 0.5-, 1.2-, or 2.5-mm aggregates embedded in an epoxy resin matrix.

| | Aggregate treatment (mm) | | | | | |
|---|---|---|---|---|---|---|
| | None | 0.5 | 1.2 | 2.5 | SED[1] | Probability |
| Frictional coefficients | | | | | | |
| Static | 0.33 | 0.42 | 0.49 | 0.74 | 0.041[2] | 0.01 |
| Sliding | 0.34 | 0.61 | 0.58 | 1.00 | 0.012[2] | <0.001 |
| Abrasion rate (mg/min) | 1.2 | 32.5 | 52.9 | 67.2 | 0.00051 | <0.001 |

[1]SED = Standard error of the difference between two means.

[2]SED of interaction between static/sliding coefficients and aggregate treatment = 0.0258 ($P < 0.001$).

rate increased in proportion to aggregate size, from treatment No aggregate (1.2 mg/min) to the largest aggregate, 2.5 mm (67.2 mg/min).

The walking speed of cows was similar for the No aggregate and 0.5-mm treatment and declined for the 1.2- and 2.5-mm aggregates (Table 2). The cows on the floors with aggregate had longer steps and slower stepping rate than those on floor with no aggregate.

At the start of the supporting phase, the carpal and metacarpophalangeal joints of the forelimb were most vertical on the surface without aggregate and least vertical on the floor with 0.5-mm aggregate. A gradual increase in erectness was observed from 1.2 to 2.5-mm aggregate. The hoof angle did not demonstrate this trend and was most erect in the 0.5-mm aggregate and least in the 1.2-mm aggregate. At the end of the support-

**Table 2**. Walking behavior, the angles of the joints of the front and hind limbs to the horizontal (S = start of stride and E = end of stride) and the arcs travelled by the joints during the support phase of a stride made by cows on floors with no aggregate or a surface application of 0.5-, 1.2-, or 2.5-mm aggregate.

| | Aggregate treatment (mm) | | | | | |
|---|---|---|---|---|---|---|
| | None | 0.5 | 1.2 | 2.5 | SED† | Probability |
| Walking rate (m/s) | 0.85 | 0.84 | 0.82 | 0.81 | 0.006 | 0.01 |
| Step length (m) | 1.30 | 1.37 | 1.35 | 1.36 | 0.004 | <0.001 |
| Stepping rate (step/s) | 0.65 | 0.61 | 0.60 | 0.59 | 0.005 | <0.001 |
| Forelimb | | | | | | |
| Elbow joint S, ° | 71.5 | 69.1 | 70.3 | 71.4 | 0.58 | 0.16 |
| Elbow joint E, ° | 120.4 | 122.2 | 121.4 | 122.1 | 0.57 | 0.38 |
| Elbow joint arc, ° | 48.9 | 53.5 | 51.1 | 50.8 | 0.75 | 0.03 |
| Carpal joint, S, ° | 108.3 | 111.5 | 109.6 | 108.6 | 0.58 | 0.03 |
| Carpal joint E, ° | 59.7 | 57.5 | 58.6 | 57.9 | 0.57 | 0.33 |
| Carpal joint arc, ° | 48.7 | 53.9 | 51.1 | 50.9 | 0.75 | 0.01 |
| Metacarpophalangeal joint S, ° | 110.2 | 113.0 | 111.2 | 111.3 | 0.35 | 0.002 |
| Metacarpophalangeal joint E, ° | 52.3 | 55.3 | 51.5 | 53.9 | 0.73 | 0.05 |
| Metacarpophalangeal joint arc, ° | 58.1 | 57.5 | 59.3 | 57.4 | 0.82 | 0.63 |
| Forefoot:floor S, ° | 132.4 | 128.4 | 133.6 | 131.3 | 0.61 | <0.001 |
| Forefoot:floor E, ° | 79.6 | 77.5 | 79.1 | 80.3 | 1.29 | 0.74 |
| Forefoot:floor arc, ° | 53.1 | 50.7 | 54.5 | 50.9 | 1.35 | 0.44 |
| Hindlimb | | | | | | |
| Stifle joint S, ° | 85.4 | 82.1 | 82.5 | 83.2 | 0.64 | 0.05 |
| Stifle joint E, ° | 140.0 | 137.5 | 139.6 | 137.0 | 0.47 | 0.004 |
| Stifle joint arc, ° | 54.8 | 55.6 | 57.1 | 53.6 | 0.68 | 0.08 |
| Tarsal joint S, ° | 94.6 | 98.0 | 97.6 | 96.3 | 0.64 | 0.04 |
| Tarsal joint E, ° | 40.0 | 42.4 | 40.4 | 43.0 | 0.46 | 0.004 |
| Tarsal joint arc, ° | 54.3 | 55.4 | 57.2 | 53.0 | 0.68 | 0.02 |
| Metatarsophalangeal joint S, ° | 119.1 | 122.1 | 123.5 | 120.4 | 0.49 | <0.001 |
| Metatarsophalangeal joint E, ° | 67.8 | 66.9 | 66.9 | 66.1 | 0.50 | 0.44 |
| Metatarsophalangeal joint arc, ° | 51.3 | 55.2 | 56.8 | 54.3 | 0.66 | 0.001 |
| Hindfoot:floor S, ° | 137.6 | 135.7 | 138.5 | 138.1 | 0.55 | 0.07 |
| Hindfoot:floor E, ° | 83.2 | 83.5 | 82.0 | 81.6 | 1.05 | 0.78 |
| Hindfoot:floor arc, ° | 54.4 | 52.3 | 56.4 | 56.5 | 1.14 | 0.23 |

†Standard error of the difference between two treatment means.

ing phase, the foreleg joint and hoof angles were not significantly affected by treatment. The arcs of the elbow and carpal joints were greatest when the cow walked on the surface with 0.5-mm aggregate. Arcs were particularly reduced for the floor with no aggregate and, to a lesser extent, 1.2- and 2.5-mm aggregate. The hoof arc was not affected by treatment.

The angles of the hindlimb joints demonstrated a similar trend to the forelimb joints at the start of the supporting phase. The stifle, tarsal, and metatarsophalangeal joints were most vertical when cows walked on the floor without aggregate, and least vertical on the floors with 0.5 or 1.2 mm aggregate. The 2.5-mm aggregate treatment response was intermediate. However, as with the forelimb, the hoof angle was most vertical when cows walked on the 0.5-mm aggregate. At the end of the supporting phase, the two upper joints of the hindlimb, the stifle, and tarsal were least vertical on the surface with no aggregate. There were no treatment effects in the metatarsophalangeal joint angles or the hoof angles at the end of the supporting phase. All three joint arcs were greatest when the cows walked on the surface with 1.2-mm aggregate, although this response was not statistically significant in the case of the stifle joint ($P = 0.078$). The arcs diminished progressively from the 1.2 to no aggregate treatments. There was no treatment effect on the hoof arc in the hindlimb joints.

## DISCUSSION

The frictional coefficient for the surface with no aggregate was less than the critical value of 0.4, below which the risk of slip increases exponentially (Webb and Nilsson, 1983), and was similar for sliding and static friction. Previous research with this apparatus found that on floors with different slurry coverings the sliding friction was less than the static friction (Phillips and Morris, 2000). In contrast, results of this experiment showed greater coefficients for sliding friction on the surfaces with aggregate. This may be due to the irregular vertical (braking) force produced when the hoof contacts large pieces of aggregate, compared with slurry where the resistance to movement provided by the slurry is constant. In the case of the slurry, the initial force required to move the object would be expected to be greater than that needed to keep it moving. Sliding measurements are believed to most accurately simulate the frictional forces acting during walking in humans (Redfern and Bidanda, 1994). For cattle, it is likely that the sliding friction most accurately reflects the risk of slip at the start of the supporting limb phase, when the hoof is gaining contact with the ground. Static friction may most accurately represent the risk of slip during the lift, since the hoof is static at this time.

Cows decreased their step length when walking on floors without aggregate. This was accompanied by a more vertical position of the upper (fore and hind) limb angles of both the fore and hind limbs at the start of the supporting phase and reduced joint angles. The two upper hindlimb joints were less vertical at the end of the supporting phase when the cows walked on the floor without aggregate, compared to surfaces with aggregate. When the cows were on the floor without aggregate they visibly hurried to complete their passage over the test floor. The question remains as to whether the more vertical nature of their upper limbs at the start of the supporting phase served to quicken their step, or to minimize the risk of slip. Since walking speed on non-aggregate floor was faster than the other treatments, it seems likely that the former explanation applies. In this study cows did not reduce their walking speed when there was a significant risk of slip ($\mu < 0.4$).

In the floor with 2.5-mm aggregate, the cows shortened their stepping rate, which resulted in the slowest walking rate. This is probably due to the increase in friction coefficients compared with the floors with the 0.5- or 1.2-mm aggregates. The reduction in the stepping rate, reduced arcs, and more vertical upper forelimb joints on this floor surface occurred while the step length was similar to the other treatments with aggregate. This suggests that cows walking on the 2.5-mm floor took longer in the movement of the hanging limb, and less time to move the supporting limb. This would reduce the time that the hoof was in contact with the floor. Sole bruising has been observed in piglets housed on floors with exposed aggregate (Mouttotou et al., 1999). The slow walking speed on this treatment suggests that it is not suitable for cow movement.

The less vertical nature of most of the fore and hind limb joints at the start of the supporting phase when the cows walked on the floor with 0.5-mm aggregate, and large joint arcs, suggests that cows found this treatment most suitable for long strides. Indeed step length was longest on this treatment, although it did not differ significantly from the other two aggregate treatments. As friction was proportionately increased by at least 0.5 and abrasion was three times as great, lengthened stride was used to increase walking rate compared with the floors having a larger aggregate. By contrast, for the low friction (no aggregate) treatment stepping rate was increased. However, increasing the joint arcs could increase the risk of slipping compared with the two larger aggregate treatments. The adaptation to reduce this risk was to keep the foot angle more vertical, while increasing the step length as much as possible by extending the upper leg at the start of the supporting phase (when the risk of slipping is low). Hence, the foot angle was most vertical for this treatment at the start of the supporting phase in both the fore and hind limbs.

## CONCLUSIONS

Floor friction has a considerable impact on the walking pattern of cows. Cows walked quickly with frequent, short steps on low friction floors ($\mu < 0.4$). As $\mu$ increased to 0.5 (mean of static and sliding friction) with aggregates of 0.5 and 1.2 mm, step length increased and the number of steps decreased in order to maintain speed. Increased $\mu$ also may increase the hanging limb phase at the expense of the supporting limb phase, to reduce friction, while maintaining a long stride. These results, together with a previously observed relationship between $\mu$ and slip frequency, suggest that the optimum coefficient of friction for cattle floors is between 0.4 and 0.5.

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