# Gait and Force Analysis of Provoked Pig Gait on Clean and Fouled Concrete Surfaces

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## *Abstract*

Gait and force analysis have proven to be useful methods in linking claw injuries to surface material conditions. To determine the relationship between claw disorder and floor properties such as friction and surface abrasiveness, the factors controlling gait must be characterised.

The effects of fouled concrete floor conditions on the gait of 10 pigs walking in a curve, using kinematics and kinetics to record gait parameters and slip frequency are described and compared with clean conditions.

Pigs adapted to fouled floor conditions by reducing their walking speed and stride length, using a higher number of 3-foot support phases and by lowering diagonality. This adaption produced lower vertical forces, a twofold reduction in propulsion and outward stabilisation force and a threefold increase in braking force, without reducing the peak utilised coefficient of friction (UCOF).

The UCOF values for both limbs of the curve walking pigs exceeded the recorded dynamic coefficient of friction and the corresponding UCOF values for pigs walking a straight line in fouled floor condition. As UCOF increased and available friction from the fouled floor surface decreased, this resulted in higher forward and backward slip frequency in both limbs for pigs walking in a curve.

Pigs provoked to walk in a curve can adapt to fouled floor condition, but if the floor is heavily fouled this adaption is not sufficient to ensure safe walking.

Keywords: pig, floor, friction, slip, concrete, kinematic and kinetic.

## Nomenclature

| | |
|---|---|
| BPN | British Pendulum Number represents the frictional property for SRT. |
| COF | Coefficient of friction; ratio between frictional and normal force, $F_{\mu}/F_N$. |
| $CW_c$ | Pigs walking a curved test aisle on concrete floor |
| Diagonality | The percentage of stride time in which a footfall of the front biped follows that of a rear biped on the same side of the body. |
| DS walk | A gait when the diagonality is between 50 and 100%. Each hind footfall is followed by the diagonally opposing fore footfall. |
| DV | Digital video |
| Duty factor | The relative value between stance and stride time. In a walk the stance duration of a limb is at least 50% of a complete stride cycle, while a run occurs when the value is less than 50%. |
| DCOF | Dynamic COF; the ratio of the horizontal and vertical forces when object are sliding relative to one another. |
| Elastomer | An elastomer is a polymer in which the stress is not proportional to the strain but if unloaded it recovers to its original status. |
| Floor properties | Friction, abrasiveness, hardness, surface profile and thermal properties etc. |
| Friction | Friction force (N) depends on the character of the mechanical and molecular interactions between the two surfaces in contact. |
| FP | Force plate. |
| GRF | Ground reaction force (N), measured with an FP. All GRFs were normalised to body weight, and therefore expressed in N $kg^{-1}$.<br>$GRF_v$ Vertical GRF<br>$GRF_{long}$ Longitudinal GRF (in the travelling direction)<br>$GRF_{lat}$ Lateral GRF |
| LS walk | Lateral sequence walk if diagonality is between 0 and 50% with the feet touch down in the order left hind, left fore, right hind, right fore. |
| PSM | Pull Slip Meter, a friction measurement device. |
| SCOF | Static COF; the ratio of the horizontal and vertical forces when objects start to slide relative to one another. |
| Slip safe | An environment where the measured DCOF is greater than the peak UCOF. |
| SRT | Slip Resistance Tester, a friction measurement device. |
| Stance time | Time (s) the foot is in contact with the ground. |
| Stride elevation | Maximum vertical displacement (m) between two consecutive foot strikes of the same foot. |
| Stride length | Horizontal displacement (m) between two consecutive foot strikes of the same foot. |
| Stride speed | Stride length/stride time, ($m/s^{-1}$). |
| Stride time | Time interval (s) between two consecutive foot strikes of the same foot. |
| $SW_c$ | Pigs walking in a straight test aisle on concrete floor. |
| Swing time | Time (s) the foot is not in contact with the ground. |
| Symmetrical gait | Gaits in which the footfalls of hind and fore feet are evenly spaced in time. |
| UCOF | Utilised COF; the ratio between the horizontal and normal components of the ground reaction forces (GRF) generated by a subject during floor foot contact determined by a force plate (FP). |

## 1. Introduction

With the frequency of foot and leg injuries increasing in pig husbandry systems (Gjein, 1994; Jörgensen, 2003; Lahrmann et al., 2003), much recent research has focused on methods for identifying the cause of the problem. Gait and force analysis have proven to be useful methods in linking claw injuries to surface material conditions, with animal gait being used as an indicator of floor properties and lameness (Applegate et al., 1988; McKee & Dumelow, 1995; Rajkondawar et al., 2002; Flower et al., 2005; van der Tol et al., 2005; Thorup et al., 2007; Bahr et al., 2008; von Wachenfelt et al., 2008, 2009).

But, in order to minimise slip and fall injuries, it is important to understand gait biomechanics (Applegate et al., 1988; Cham & Redfern, 2002a) and the factors causing slip and fall accidents and their interactions with environmental factors (Perkins, 1978; Strandberg & Lanshammar, 1981; Redfern & DiPasquale, 1997; Hanson et al., 1999). Gait biomechanics and the state of the pig sensory and neuromuscular system are animal factors.

Among the most important environmental factors are the floor properties of the housing. Such properties include surface friction coefficient (COF), abrasiveness and softness (Webb & Nilsson, 1983; Nilsson, 1988), and interactions with the pig claw (Webb & Nilsson, 1983; Webb, 1984; Applegate et al., 1988; McKee & Dumelow, 1995; Thorup et al., 2007).

On horizontal surfaces the COF is determined by the ratio of the horizontal and vertical forces. It is referred to as static COF (SCOF), just before and just when objects start to slide relative to one another, and as the dynamic COF (DCOF) during sliding.

In most cases, slip and fall accidents occur from an inability to adapt to floor conditions. An increasingly slippery floor will result in a high risk of slipping if the subject does not alter its gait (Redfern & DiPasquale, 1997). Foot forces that are generated when a foot comes in contact with the ground require friction to prevent slip (Hanson et al., 1999).

The friction that a subject requires from the floor surface during walking, or the coefficient of friction (UCOF) utilised, can be determined from force plate (FP) recordings of the ground reaction forces (GRF). The UCOF is defined as the ratio between the horizontal and normal components of the GRF generated by a subject during floor foot contact (Redfern et al., 2001). The probability of slip occurs, either when the UCOF of the subject increases, or when the available friction from the floor surface decreases (Hanson et al., 1999).

In pig gait, the COF depends on claw properties, flooring and the surface (e.g. floor conditions such as dry, wet or manure-fouled). Typical COF values for cows range from 0.25 to 0.55 depending on floor conditions and testing method (Webb & Nilsson, 1983; Phillips & Morris, 2001). A sufficient COF value for animals standing or in locomotion is suggested to be at least 0.35-0.40 (Webb & Nilsson, 1983).

Cham & Redfern (2002a) found that a human subject used both postural and temporal gait adaptions to reduce the risk of slipping when anticipating slippery floor conditions. Hanson et al. (1999) reasoned that to make the environment slip-safe, it is necessary to design floors where the probability of slip and fall would be extremely low, for which the measured DCOF was greater than the peak UCOF. However, they concluded that this is influenced not only by the shoe/foot, floor and contaminant exposure, but also by the types of movements required by the subject.

For pigs in intensive pig production, often housed on concrete floors, the pig pen often involves competition in relatively small areas, where the floors could be wet, fouled and sometimes degraded (De Belie, 1997). To the best of our knowledge the UCOF values for required pig movements in pig pens are unknown.

In pigs walking a straight line, one study kinematically analysed pig gait and number of pig slips on wet concrete surfaces with different coefficients of friction (Applegate et al., 1988), but no previous study has presented pig gait based on kinematic and kinetic analysis on a friction-documented pig floor with corresponding slip frequency.

Studying pigs that are induced to walk in a curve as an external provocation in which their movements are recorded, could provide answers about how and to what extent the pigs adapt to a provoked gait and how the vertical and horizontal forces and the slip frequency are affected.

The objectives of this study were to characterise provoked pig gait (walking in a curve) on a clean solid concrete surface and to evaluate the effect of fouled surface on pig gait by use of kinematics and kinetics. The hypothesis was that pigs would adapt their gait to the provoked condition but that this adaptation would not be sufficient to avoid slipping in fouled floor condition.

## 2. Materials and Methods

### 2.1 Animals

Ten Swedish Landrace pigs, 3 barrows and 7 gilts, were used in the study. Before and after the test, their claws were examined according to a standard procedure (Brooks et al., 1977) by a veterinary surgeon who also subjectively judged the pigs to have healthy claws and gait. The average animal weight during the test period (4 d) was 101 kg (sd = 18 kg). The subject pigs and the test procedures were described by von Wachenfelt et al. (2008, 2009).

### 2.2 Experimental set-up

A test aisle was built with a 30° right-hand curve placed immediately after a force place (Fig. 1). The test aisle was covered by replaceable slabs, described in von Wachenfelt et al. (2009). Pig gait on the test aisle was recorded by a built-in force plate (FP) lying flush with the paved surface and a perpendicularly placed digital video (DV) camera. The camera view covered 2.3 m of the centre line in the test aisle. The test aisle and the FP were covered with the same concrete flooring material. Two concrete surface conditions were tested, clean and artificially fouled by pig faeces as described in von Wachenfelt et al. (2008). The DV data were collected at 60 Hz by an IEEE 1394 camera with 656*490 pixels and FP data were sampled at 1 kHz.

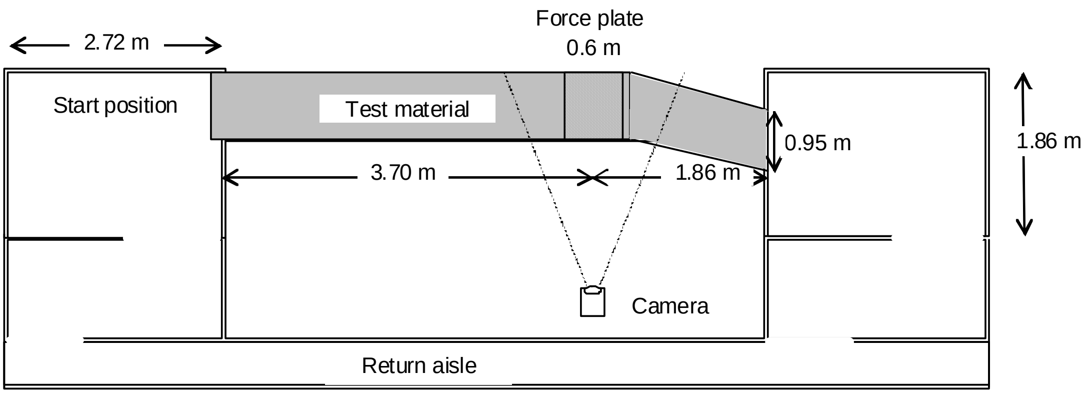


Fig. 1. Plan of the test area.

### 2.3 Experiment

The pigs walked the test aisle individually at a self-chosen speed. The number of passages for each pig was 10 per replicate. Two replicates were conducted for each floor condition. The pigs were randomly selected for each replicate and in general, only data from the last 6 passages were used, as this gave the pigs time to become accustomed to the floor conditions before sampling. A successful passage by a provoked pig was defined as a pig walking at a steady pace without stopping or jumping, placing its fore or hind claws or both claws entirely on the force plate, but separated in time. In some passages more than one fore and hind limb could be fully registered. A total of 4 and 2.5% of the passages in clean and fouled floor conditions, respectively, were unsuccessful and were replaced by new passages. The average time to conclude the 10 passages was 11 min per pig. The indoor temperature was 17 ± 3°C and the relative humidity 54 ± 13%.

Five positions of the animal were digitised in each DV frame: the fore and hind claw tip positions and either nose tip or tail root positions. The nose tip/tail root positions of the animal were used to calculate the walking speed and the claw tip positions were used in determining stride parameters such as stride length, stride time, stride speed, swing time, stance time, stride elevation together with limb support phases, gait symmetry, diagonality and duty factor. The stride parameters and their definitions have been described previously (von Wachenfelt et al., 2008). The FP recorded three GRFs from the pigs, a vertical GRF component ($GRF_v$), and two horizontal components, GRF longitudinal ($GRF_{long}$) and GRF lateral ($GRF_{lat}$), as described in von Wachenfelt et al. (2009).

Two friction test devices, a horizontal pull slip meter (PSM) and a dynamic pendulum impact-type tester, (SRT) (ASTM, 1993) recorded the coefficient of friction (COF) and British Pendulum Number (BPN) of the flooring (von Wachenfelt et al., 2009). The test body of both the pendulum slider and the horizontal pull slip meter were covered by a piece of leather corresponding to pig claw hardness and friction (Bring, 1964). The leather used was standard commercial leather (ISS, 2003).

## 2.4 Data processing

The definition and processing of the stride, force and friction data were as described by von Wachenfelt et al. (2008, 2009). Each stride and GRF parameter was calculated as an average per pig and floor condition and for both front and hind limbs. The statistical basis for the calculation was the average of 10 pigs per floor condition.

Slip frequency was defined as the number of slips in relation to the total number of stances per pig and limb. The number of slips, slip length and slip time were recorded from DV data based on a complete stride for each passage and all limbs. The slips were divided into forward and backward slips. A slip below a threshold of 10 mm was referred to as micro-slip and was disregarded, whereas a slip above 10 mm was characterised as a slip from which the subject recovered or did not recover from (Perkins, 1978; Applegate et al, 1988; Cham & Redfern, 2002b). No slips occurred from which the pigs fell and did not recover, i.e. they could not continue the walk.

## 2.5 Statistics

Paired t-test was used to compare differences within and between floor conditions and to examine differences between fore and hind limbs within stride, force and friction data for pigs walking a straight line and walking a curve. The data were tested for normal distribution. The probability limits for evaluating statistical significance were: * = $p<0.05$; ** = $p<0.01$; *** = $p<0.001$. Results are presented as mean and standard deviation (SD).

# 3. Results

## 3.1 Gait differences due to floor condition in walking in a curve

All data were normally distributed. In clean floor condition, $CW_c$ pigs had a walking speed of 1.10 $ms^{-1}$ and a stride length of 0.95 m, which were both 9% higher and longer than for $CW_c$ pigs in fouled floor condition. Stride time, swing and stance time and stride elevation did not differ between floor conditions. The effects of floor conditions on pig gait parameters are given in Table 1.

Table 1. Stride characteristics of 10 pigs provoked to walk in a curve. Comparison between Fore and Hind limbs and between Clean and Fouled concrete floor conditions (number of readings (n), mean and standard deviation (SD))

| Parameter | Conditions | | | | | Limb | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Clean | | Fouled | | | Fore | | Hind | |
| | n | Mean (S.D.) | n | Mean (S.D.) | p[1] | n | Mean (S.D.) | n | Mean (S.D.) | p[1] |
| Walking speed, m/s | 474 | 1.10 (0.17) | 471 | 1.00 (0.19) | * | | | | | |
| Stride length, m | 474 | 0.95 (0.06) | 471 | 0.86 (0.06) | *** | | | | | |
| Stride time, s | 474 | 0.89 (0.16) | 471 | 0.86 (0.13) | ns | | | | | |
| Stride speed, m/s | 474 | 1.11 (0.16) | 471 | 1.00 (0.19) | * | | | | | |
| Swing time, s | 474 | 0.41 (0.04) | 471 | 0.41 (0.04) | ns | | | | | |
| Swing/stance time ratio | 472 | 0.90 (0.12) | 470 | 0.89 (0.17) | ns | 472 | 0.93 (0.15) | 470 | 0.86 (0.14) | ** |
| Stance time, s | 472 | 0.47 (0.12) | 470 | 0.48 (0.12) | ns | 471 | 0.46 (0.11) | 471 | 0.49 (0.12) | ** |
| Max stride elevation, m | 480 | 0.07 (0.01) | 474 | 0.06 (0.01) | ns | 478 | 0.07 (0.01) | 478 | 0.06 (0.01) | ns |
| Number of 1-foot supports | 115 | 4.42 (2.76) | 117 | 1.85 (2.29) | *** | | | | | |
| Number of 2-foot supports | 115 | 77.38 (11.04) | 117 | 67.71 (7.31) | ** | | | | | |
| Number of 3-foot supports | 115 | 17.86 (12.70) | 117 | 28.64 (8.64) | ** | | | | | |
| Number of 4-foot supports | 115 | 0.19 (0.36) | 117 | 1.74 (1.36) | ** | | | | | |
| Symmetry, % | 115 | 50.57 (0.57) | 117 | 50.72 (0.74) | ns | | | | | |
| Diagonality, % | 115 | 86.04 (6.09) | 117 | 81.06 (5.89) | * | | | | | |
| Duty factor, % | 474 | 53.07 (3.65) | 471 | 53.69 (3.74) | ns | | | | | |

1) Probability limits for evaluating statistical significance: ns = non-significant, * = p<0.05; ** = p<0.01; *** = p<0.001

In both floor conditions, the $CW_c$ pig walk was characterised by a four-beat symmetric gait distinguished by alternating 2- or 3-foot support phases. Observed single or 4-foot support phases were less than 4 and 2 %, respectively. The number of 2-foot support phases decreased from 77 to 68% in fouled floor condition compared with clean and the diagonality decreased from 86 to 82%, while the number of 3-foot support phases increased from 18 to 29%. The symmetrical pig gait, with high diagonality and duty factor, resulted in a gait pattern of a clear diagonal-sequence (DS) walk, which was maintained with both floor conditions (Fig. 2).

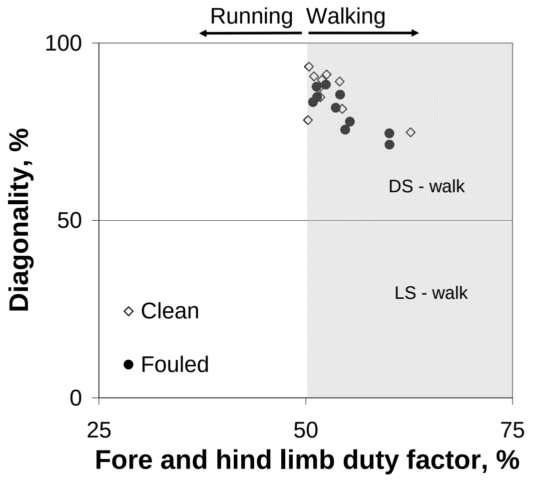


Fig. 2. Hildebrand diagram of diagonality (percentage of the cycle period by which the hind footfall precedes the fore footfall on the same side) against mean duty factor (stance period of fore and hind foot as a percentage of gait cycle) for symmetrical gaits of 10 pigs walking in a curve on concrete. Open squares represent gait cycles on clean test aisle; solid circles represent cycles on fouled test aisle. The lower right area of the diagram represents lateral-sequence (LS) walking gaits and upper right area diagonal-sequence (DS) walking gaits (adapted from Lemelin et al., 2003).

Vertical and resultant horizontal GRFs for fore and hind limbs from the mean of 10 curve walking pigs ($CW_c$) on clean and fouled concrete are illustrated in Fig. 3. The mean and peak $GRF_v$ applied decreased by 5 and 15% for fore and hind limbs respectively in fouled floor condition, while in fore limbs the time of peak vertical force occurred 13% later than mid-stance (half-stance time) compared with 8% in clean condition. The hind limb applied full vertical force at mid-stance under clean floor conditions, but with fouled floor conditions the hind limbs applied full force 10% before mid-stance (Table 2).

Table 2. Force characteristics of 10 pigs provoked to walk in a curve. Comparison between fore (F) and hind (H) limbs and between Clean and Fouled concrete floor conditions (number of readings (n), mean and standard deviation (S.D.))

| Parameter | Limb | Floor conditions Clean n | Mean (SD) | p[2] | Fouled n | Mean (SD) | p[2] | p[3] |
|---|---|---|---|---|---|---|---|---|
| Mean $GRF_v$ ($Nkg^{-1}$)[1] | F[2] | 135 | 5.99 (0.36) | *** | 137 | 5.21 (0.37) | *** | *** |
| | H[2] | 135 | 3.82 (0.48) | | 144 | 3.62 (0.43) | | * |
| Peak $GRF_v$ ($Nkg^{-1}$)[1] | F | 135 | 9.73 (0.84) | *** | 137 | 8.21 (0.72) | *** | *** |
| | H | 135 | 5.80 (0.99) | | 144 | 5.24 (0.79) | | ** |
| Timing of peak $GRF_v$ (s)[1] | F | 135 | 0.17 (0.04) | * | 137 | 0.22 (0.05) | *** | *** |
| | H | 135 | 0.15 (0.03) | | 144 | 0.16 (0.03) | | ns |
| Peak $GRF_{long}$ ($Nkg^{-1}$)[1] | F | 132 | 0.31 (0.14) | ** | 137 | 0.17 (0.13) | ** | ** |
| | H | 135 | 0.62 (0.19) | | 139 | 0.42 (0.14) | | ** |
| Minimum $GRF_{long}$ ($Nkg^{-1}$)[1] | F | 132 | -0.68 (0.07) | *** | 137 | -1.19 (0.15) | *** | *** |
| | H | 135 | -0.46 (0.06) | | 139 | -0.72 (0.14) | | *** |
| Peak $GRF_{lat}$ ($Nkg^{-1}$)[1] | F | 135 | 0.08 (0.06) | ns | 136 | 0.09 (0.03) | ** | ns |
| | H | 134 | 0.04 (0.05) | | 138 | 0.02 (0.02) | | ns |
| Minimum $GRF_{lat}$ ($Nkg^{-1}$)[1] | F | 135 | -0.57 (0.20) | ** | 136 | -0.39 (0.14) | * | ** |
| | H | 134 | -0.25 (0.08) | | 138 | -0.26 (0.07) | | ns |
| Peak UCOF | F | 135 | 0.50 (0.09) | ns | 137 | 0.57 (0.14) | ns | ns |
| | H | 135 | 0.57 (0.15) | | 139 | 0.56 (0.19) | | ns |

1) Normalised to body weight
2) Significance level comparing fore and hind limbs: ns = non-significant; * = p<0.05; ** = p<0.01; *** = p<0.001
3) Significance level comparing material conditions

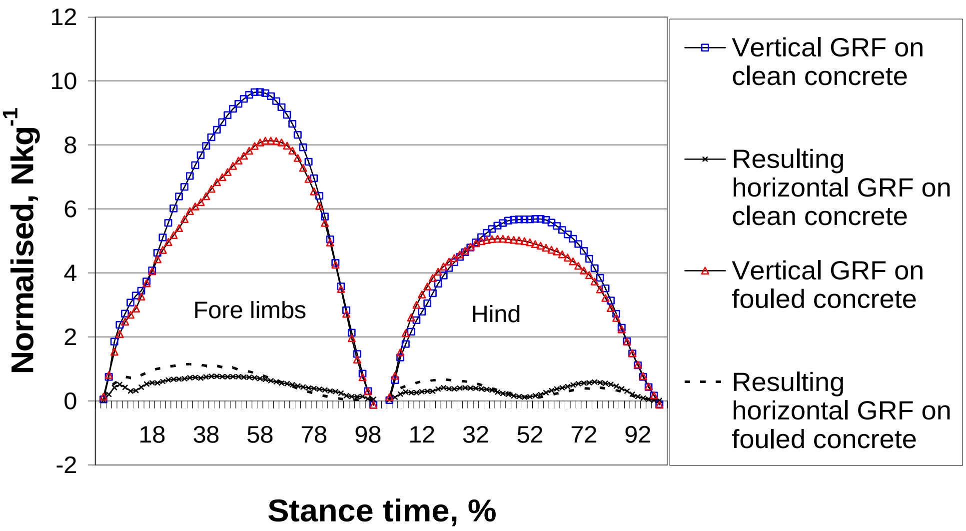


Fig. 3. Vertical and resultant horizontal GRF's for fore and hind limbs from the mean of 10 pigs walking in a curve on clean and fouled concrete.

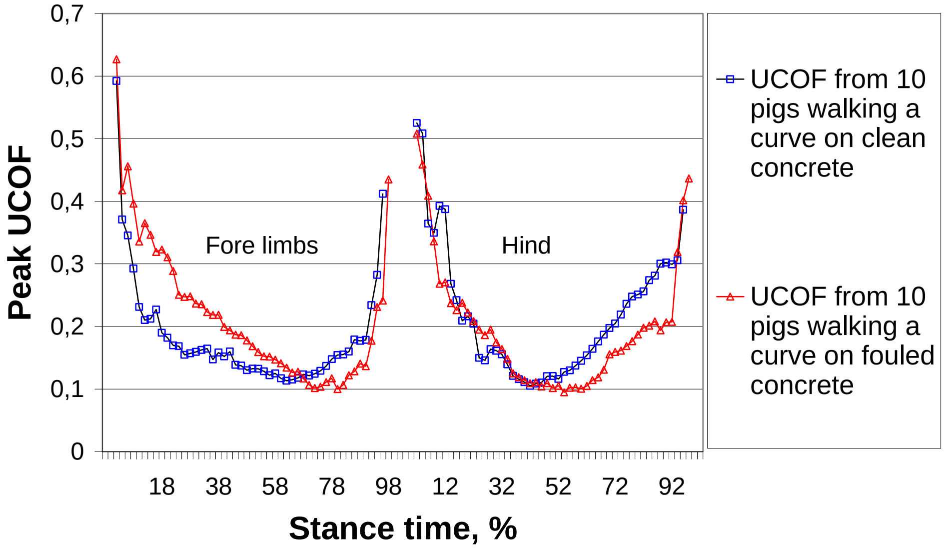


Fig. 4. Peak UCOF values for fore and hind limbs from the mean of 10 pigs walking in a curve on clean and fouled concrete. Values at the very start and end of the stance phase were discarded to avoid 'instability' regions when both shear and normal forces approach zero.

The minimum $GRF_{long}$ (braking force) applied in fouled floor conditions increased by 75 and 57% for fore and hind limbs respectively compared with clean floor conditions. For the minimum $GRF_{lat}$, the decrease on fouled floors was only significant for fore limbs.

The peak $GRF_{long}$ (propulsion force) showed a significant reduction for fore (45%) and hind (32%) limbs between clean and fouled floor conditions, while peak $GRF_{lat}$ values were consistent for both limbs. Peak UCOF of both fore and hind limbs was consistent in both floor conditions, Fig. 4.

Table 3. Coefficients of static friction (SCOF), dynamic friction (DCOF) and skid resistance (BPN) for the floorings tested in the laboratory and the pig house experiment (PSM: n = 10, SRT: n = 15)

| Test method | SCOF[3] Mean (SD) | p[5] | DCOF[3] Mean (SD) | p[5] | BPN[4] Mean (SD) | p[5] | Temperature °C; Humidity % mean |
|---|---|---|---|---|---|---|---|
| *Clean* | | | | | | | |
| PSM-leather[1] | 0.74 (0.06) | * | 0.63 (0.04) | *** | | | 19.4 ± 0.2; 32 |
| SRT-leather[2] | | | | | 80.6 (2.6) | *** | 20.4 ±0.4; 67 |
| SRT-rubber | | | | | 85.2 (1.7) | *** | 20.4 ±0.4; 67 |
| *Fouled* | | | | | | | |
| PSM-leather | 0.65 (0.05) | | 0.45 (0.02) | | | | 19.4 ± 0.2; 32 |
| SRT-leather | | | | | 42.2 (1.8) | | 20.4 ±0.4; 67 |
| SRT-rubber | | | | | 50.9 (1.4) | | 20.4 ± 0.4; 67 |

1) PSM-leather = PSM with leather covered test body.
2) SRT-leather = SRT with leather covered test body.
3) Laboratory experiment
4) Pig house experiment
5) Probability limits for evaluating statistical significance: * = p<0.05; ** = p<0.01; *** = p<0.001; ns= non significant

### 3.2 Gait difference between fore and hind limbs in walking in a curve

The hind limbs of $CW_c$ pigs had a lower swing-stance time ratio and higher stance time than fore limbs, while stride elevation was consistent in both floor conditions (Table 1).

The mean and peak $GRF_v$ applied were 44% and 68% higher, respectively, for fore limbs than for hind limbs in both floor conditions, while the time of $GRF_v$ during stance occurred earlier for hind limbs than for fore limbs with both floor conditions (Table 2).

Peak $GRF_{long}$ was 50 and 60% lower for fore limbs than for hind limbs in clean and fouled floor conditions, respectively, while in fouled floor conditions the peak $GRF_{lat}$ of fore limbs exceeded that of hind limbs. In clean floor condition, fore limbs utilised 48% more minimum $GRF_{long}$ than hind limbs, whereas in fouled floor condition this difference in braking force increased to 65%. The minimum $GRF_{lat}$ applied by fore limbs was 2.3 and 1.5 times higher than for hind limbs in clean and fouled floor conditions, respectively. Regarding peak UCOF, there was no difference between fore and hind limbs in either of the floor conditions.

### 3.3 Floor friction and slip

With the PSM measuring device, SCOF was higher than DCOF and SCOF was highest in clean floor condition (Table 3). Significant differences in SCOF and DCOF were found between clean and fouled floor conditions for PSM-leather, and for both SRT-leather and SRT-rubber.

Table 4. Slip characteristics (>10mm) of 10 pigs provoked to walk in fouled concrete floor conditions. Comparison between fore (F) and hind (H) limbs and between walking a straight line and a curve (number of readings (n), mean and standard deviation (SD))

| Parameter | Straight line | | | | Curve | | | |
|---|---|---|---|---|---|---|---|---|
| | n | Limb | Mean (SD) | p[1] | n | Mean (SD) | p[1] | p[1] |
| Backward slip time, s | 117 | F | 0.01 (0.02) | ns | 117 | 0.06 (0.05) | ** | *** |
| | 117 | H | 0.03 (0.07) | | 117 | 0.14 (0.06) | | *** |
| Backward slip length, m | 117 | F | 0.00 (0.00) | ns | 117 | -0.02 (0.01) | * | *** |
| | 117 | H | -0.02 (0.09) | | 117 | -0.04 (0.03) | | ns |
| Backward slip frequency, % | 117 | F | 0.00 (0.00) | ns | 117 | 30.01 (18.80) | *** | *** |
| | 117 | H | 2.29 (5.65) | | 117 | 45.21 (19.65) | | *** |
| Forward slip time, s | 117 | F | 0.22 (0.08) | ns | 117 | 0.22 (0.09) | *** | ns |
| | 117 | H | 0.21 (0.14) | | 117 | 0.15 (0.09) | | ns |
| Forward slip length, m | 117 | F | 0.07 (0.06) | ns | 117 | 0.09 (0.05) | * | ns |
| | 117 | H | 0.08 (0.12) | | 117 | 0.05 (0.05) | | ns |
| Forward slip frequency, % | 117 | F | 31.44 (19.04) | * | 117 | 82.14 (25.86) | *** | *** |
| | 117 | H | 18.65 (15.84) | | 117 | 43.09 (17.83) | | *** |

1) Probability limits for evaluating statistical significance: ns= non significant; * = p<0.05; ** = p<0.01; *** = p<0.001

In general, backward slip time, length and frequency were higher for hind limbs and forward slip time, length and frequency were higher for fore limbs. Backward and forward slip lengths were of the same order of magnitude and backward and forward slip frequency was consistent for hind limbs. However, for fore limbs the forward slip frequency was more than double the backward slip frequency (Figs. 5 and 6, Table 4). In clean floor condition no slips greater than 10 mm were observed.

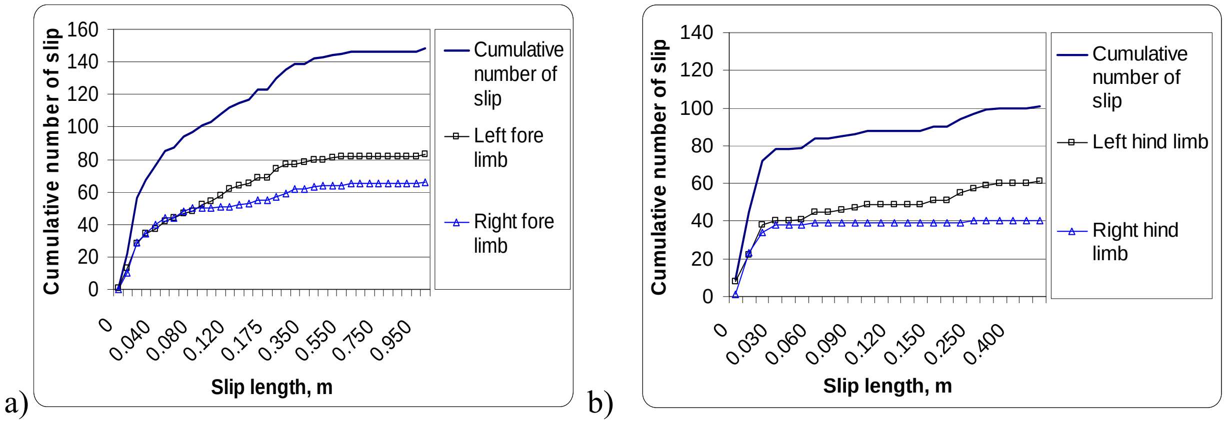


Fig. 5. Number of slips for 10 pigs walking a curve (30° to the right) in fouled floor conditions. a) fore limbs, 193 slips >10 mm in 234 passages on the test aisle, b) hind limbs, 101 slips > 10 mm in 234 passages on the test aisle.

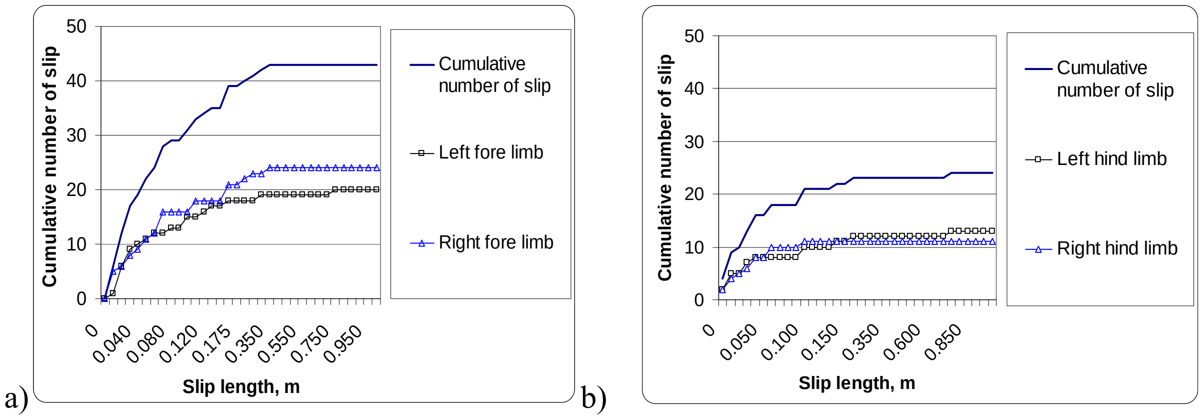


Fig. 6. Number of slips for 10 pigs at straight walk in fouled floor conditions. a) fore limbs, 43 slips >10 mm in 235 passages on the test aisle, b) hind limbs, 24 slips > 10 mm in 233 passages on the test aisle. Data assessed from von Wachenfelt et al. (2009).

# 4. Discussion

This study enables a comparison to be made of the friction needed and the friction provided by a floor for provoked pigs walking a curve. The moderate right-hand curve design was primarily chosen to give the pigs a fully identified test aisle from start to end, i.e the pigs could walk at a self-chosen speed. If we had chosen a stronger curve for the test aisle, we would probably have had more stops and refusals in the pig walk. A ramp angle test would have been a more complicated approach in handling the pigs and in experiment set up. The mean body weight of the pigs was the same during test period, which means that the differences in gait were not caused by differences in body size.

## 4.1 Main findings

The main finding of this study was that the pigs adapted to the provoked conditions but the adaptation was not sufficient enough to avoid slipping in fouled floor conditions. A moderate gait adaption was applied by the curve walking pigs on concrete (CWc) in fouled floor conditions, with reduced walking speed and stride length, a higher number of 3-foot support phases, and lower diagonality.

An increased body weight was found in CWc fore limbs in both floor conditions compared with pigs walking a straight line (SWc) (von Wachenfelt et al., 2009). The CWc pigs utilised more braking force on the fore limbs than on the hind limbs, which increased in fouled floor conditions. Under fouled floor condition the CWc pigs use more braking force in fore and hind limbs, respectively than SWc pigs. Thus, UCOF values for both limbs of the CWc pigs exceeded the recorded DCOF and the corresponding values of SWc found under fouled floor conditions, which resulted in higher CWc forward and backward slip frequencies in both limbs as UCOF increased and the available friction from the fouled floor surface decreased (Hansson et al., 1999).

## 4.2 Kinematics

### *4.2.1 Gait differences due to floor conditions*

The symmetrical walking pattern, with alternating two- and three-foot support phases, exhibited by the pigs in the present study was similar to the walk of pigs reported by Thorup et al. (2007) and von Wachenfelt et al. (2008). The walking pattern corresponded to the walk of dogs (Hottinger et al., 1996), cows (Flower et al., 2005) and horses (Hodson et al., 2001). In both floor conditions the pigs used a clear DS walk in which the hind foot touched down slightly after the contra-lateral foot (Fig. 2).

In clean floor conditions, the $CW_c$ pigs had a cautious but confident walk and applied a moderate gait pattern adaption compared to SWc pigs (von Wachenfelt et al., 2008). In fouled floor conditions the moderate $CW_c$ gait adaption was observed through reduced walking speed and stride length, a higher number of 3-foot support phases and lower diagonality. Comparable gait adaptions in straight walking in fouled floor conditions have been reported for humans (Cham & Redfern, 2002a), cows (Phillips & Morris, 2000; Telezhenko & Bergsten, 2005) and pigs (Thorup et al., 2007; von Wachenfelt et al., 2008), but also for humans descending stairs (Cham & Redfern, 2002a).

### *4.2.2 Gait differences between fore and hind limbs*

In their adaption of gait to fouled floor conditions, $CW_c$ pigs prolonged their hind stance phase compared with SWc pigs (Applegate et al., 1988; Thorup et al., 2007; von Wachenfelt et al., 2008), probably to increase stability, as the hind limb is closer to the centre of gravity of the body (Applegate et al., 1988). An increased number of 3-feet support phases and lower diagonality would increase the size of the animal support polygon and make its stance more stable in moving forward (Cartmill et al., 2002; von Wachenfelt et al., 2008).

The size of CWc gait adaptation in fouled floor condition is illustrated by comparing with corresponding SWc pigs (von Wachenfelt et al., 2008). The CWc pigs reduced their walking speed compared to SWc by 24%, prolonged swing and stance time 58 and 50% respectively, reduced the number of 2-foot supports by 14%, and increased the number of 3-foot supports three-fold and diagonality by approx. 32% .

## 4.3 Kinetics

The gait adaption in CWc fouled floor conditions resulted in a reduction for a majority of GRF parameters in both limbs such as, mean, peak and timing of peak $GRF_v$, peak $GRF_{long}$ (propulsion force) and min $GRF_{lat}$ compared to clean while peak $GRF_{lat}$ and UCOF remained consistent. Only min $GRF_{long}$ (braking force) increased in fouled floor conditions.

### *4.3.1 Gait differences due to floor condition and difference between fore and hind limbs*

In comparison with SWc pigs there is an additional horizontal force (centripetal force) acting on $CW_c$ pigs (van der Tol et al., 2005). The $CW_c$ pigs delivered higher mean and peak $GRF_v$ in fore limbs in clean floor conditions than $SW_c$ pigs (von Wachenfelt et al., 2009), but the corresponding values were not significant for hind limbs. In fouled floor conditions the hind limb mean $GRF_v$ was lower in $CW_c$ pigs than in $SW_c$ pigs (no centripetal force) (von Wachenfelt et al., 2009), which could mean that weight is transferred to the $CW_c$ fore limbs.

$CW_c$ pigs carried approx. 60% of their body weight on their fore limbs (mean $GRF_v$). The peak $GRF_v$ generated a weight distribution of approx. 62% on the fore limbs (Table 2) compared with 56 and 57% body weight respectively in $SW_c$ pigs (Thorup et al., 2007; von Wachenfelt et al., 2009).

The CWc pigs utilised more braking force on the fore limbs than on the hind limbs, which increased in fouled floor condition. In fouled floor condition the CWc pigs use 75 and 36% more braking force in fore and hind limbs, respectively than $SW_c$ pigs (von Wachenfelt et al., 2009). The hind limb braking forces in fouled floor conditions in the present study agree with corresponding results from $SW_c$ pigs (Thorup et al., 2007), but CWc fore limb braking force values were 34% higher than for SWc (Thorup et al., 2007) fore limbs. The CWc propulsion values correspond with previous findings (von Wachenfelt et al., 2009), but propulsion for $SW_c$ pigs (von Wachenfelt et al., 2009) were lower in the fore limbs and approx. consistent with previous data (Thorup et al., 2007) in the hind limbs. These discrepancies may be attributable to different walking speed and body weight between the studies.

The exerted lateral horizontal forces (peak and min $GRF_{lat}$) demostrate the stabilisation effort needed to maintain the travelling direction of the moving body. The small differences in peak $GRF_{lat}$ indicates that in both clean and fouled floor conditions, $CW_c$ pigs did not choose to restrict their lateral stabilising forces in order to maintain stability. However, in fouled floor conditions $CW_c$ pigs increased their stabilisation efforts for fore limbs compared with $SW_c$ pigs (von Wachenfelt et al., 2009).

### *4.3.2 Utilised coefficient of friction*

The UCOF values for fore limbs in Fig. 4 are surprising compared to corresponding values for SWc pigs (Thorup et al., 2007; von Wachenfelt et al., 2009) where lowered walking speed and the fouled floor conditions had a decreasing effect on UCOF. The CWc pigs evolved consistantly high UCOF values (>0.50) in both limbs and floor conditions. The gait adaption of the CWc pigs is clearly shown in Fig. 3, where the GRFv decreased while the resulting horizontal force increased in the first part of the stance phase for both limbs in fouled floor conditions compared to clean, which coinsides with limb braking. In the second part of the stance phase the hind limb propulsion is most evident especially in clean floor condition. In order to reduce impact at toe-on, the pigs also delayed the timing of peak GRFv, especially for fore limbs in fouled condition, as shown in previous study (von Wachenfelt et al., 2009), Fig. 3.

van der Tol et al. (2005) compared GRF and UCOF values for fore and hind limbs of cows walking in a straight line and walking in a curve and related this to the stance time corresponding to Fig. 3 and 4. The straight line GRFv showed two local maxima with a minimum in between, but for cows walking in a curve the GRFv maxima and the minima were not as evident, which corresponds with the GRFv for the CWc pigs in the present study. The resulting horizontal GRF of the fore limb of the curve walking cows (van der Tol et al., 2005) had a higher amplitude at 20% of stance phase and had a similar high amplitude at 85% of the stance phase compared to cows walking straight. A corresponding but lower amplitude was found in the CWc pigs at corresponding 20 and 85% of stance phase, especially in fouled floor conditions, Fig 3.

The lower walking speed on the fouled flooring can contribute to a reduction in UCOF values, as reported by Cham & Redfern (2002a), Powers et al. (2002). When comparing UCOF during different walking tasks for humans, Burnfield et al. (2005) found that healthy adults aged 20 to 40 years had a mean peak UCOF of 0.48 when negotiating a 90° turn, while the mean peak UCOF of level walking was 0.23 for clean floor conditions. However, van der Tol et al. (2005) found that the UCOF for cows walking a 90° curve (FP placed in the middle of the curve) in dry floor condition remained high (0.40) for almost the entire stance phase and the highest recorded UCOF was 0.80 during the heel strike phase during stopping tests.

In the present study the FP was placed just before the curve, registering the moment of curve adaption, which could explain the high CWc peak UCOF level at toe-on and toe-off compared with SWc pigs (Thorup et al., 2007; von Wachenfelt et al., 2009) and the absence of a consistantly high UCOF level during stance time in CWc pigs as shown by van der Tol et al. (2005).

## 4.4 Floor friction and slip

The SRT value of fouled floor conditions in the present study, approx. 42 BPN, was considerably lower that in the Applegate et al. (1988) study, but the PSM COF values fell almost within range of COF values reported by Thorup et al. (2007). The BPN values in the present study differed from those reported by von Wachenfelt et al. (2009); most likely due to the fact that SRT measurements are temperature-dependent. In the present study the UCOF exceeds the recorded PSM DCOF values in both fore and hind limbs at toe-on and toe-off, which also can be seen in high forward and backward slip frequencies.

The risk of slipping forward was greatest in fore limbs, according to Applegate et al. (1988). The forward momentum maintains the body weight on the leading foot (Redfern et al., 2001), which also uses the largest braking force and set the walking direction. The risk of slipping backwards is greatest for the limbs that have the highest propulsion force, i.e. the hind limbs.

The slip frequency for pigs walking a curve in fouled floor condition, where the hind limbs have a rather consistent slip frequency compared with the fore limbs, are in the first instance due to an increased friction demand walking a curve (van der Tool et al., 2005; Burnfield et al., 2005) where the UCOF increase depends on increasing braking forces for the limb at toe-on and propulsion force at toe–off to maintain the travelling direction of the moving body. Secondly, the slip frequency depends on the decreasing friction from a fouled floor surface (Hanson et al., 1999).

Applegate et al. (1988) found that forward slips are very small with 77% and 79% < 1 mm in magnitude for fore and hind limbs respectively. These slips are often referred to as micro-slips (Redfern et al., 2001) and occur without the knowledge of the ‘walker’. In the Applegate et al. (1988) study, 97% of forward front-foot slips were < 5 mm and all rear forward slips were < 3 mm long, while 95.8% of backward slips were < 2 mm long. $CW_c$ pig slip length and frequency were higher than those for pigs walking a straight line reported by Applegate et al. (1988), probably due to less friction (von Wachenfelt et al., 2009). Applegate et al. (1988) also reported that fore limbs were more affected by surface conditions than hind, and pointed out that fore limbs at toe-on lie further from the centre of gravity of the body than the hind limbs, which would give the fore limbs more exposure to horizontal forces, resulting in more slips for the fore limbs Fig. 5.

## 4.5 Gait adaption

In pigs, the strategies to avoid slipping and falling are very much the same as those reported in humans by Cham & Redfern (2002a), where a significant reduction in peak UCOF occurred during trials when the subject anticipated slippery surfaces and attempted posture control. In animals this involves more 3-foot support phases and lowered diagonality. Thus, the biomechanics of pig walking are subject to the perceptions of the environment by the individual, as descibed for humans by Grönquist et al. (2003).

In this study, the pigs responded to the provocation by adapting to walking in a curve, but when this was combined with fouled floor conditions the probability of slip and fall was also determined by the movements of the pig through the curve, or the extent to which the frictional properties of the floor were utilised by the pigs, as described for humans by Hanson et al. (1999).

In clean floor conditions, walking pigs utilise the frictional property of floors to the full extent (Thorup et al., 2007; von Wachenfelt et al 2008b). However, if the pigs are provoked by walking in a curve and the floor is fouled, adaption by the pigs to floor conditions is not sufficient to ensure walking safety.

Considering the results of this study, pen design should reconsider obstacles that could result in fast and uncontrolled animal movements, particularly in combination with fouled floor surfaces. Pen design should be based on exerted forces for required animal movements in the design of feeding, drinking, lying and dunging areas, as well as animal transport aisles.

## 6. Conclusions

In clean floor conditions, pigs provoked into walking in a curved test aisle were more cautious than pigs walking along a straight test aisle. Their gaits were characterised by symmetrical alternating two- and three-foot support phase with a high rate of diagonality. Pigs walking in a curve on a clean floor increased their body weight on the fore limbs by 5% compared with pigs walking a straight line. They utilised 48% more braking force on the fore limbs than on the hind limbs, which increased to 65% in fouled floor condition. In clean floor conditions, pigs walking in a curve used less braking force than pigs walking in a straight line, but in fouled floor conditions pigs walking in a curve used 75 and 36% more braking force in fore and hind limbs, respectively than pigs walking in a straight line.

Pigs adapted to fouled floor condition by reducing walking speed and stride length, a higher number of 3-foot support phases and lower diagonality. This adaption resulted in lower vertical forces, a two-fold reduction in propulsion and outward stabilisation force but a threefold increase in braking force, without peak UCOF reduction in fouled floor condition.

The UCOF values for both limbs of the curve walking pigs exceeded recorded DCOF and corresponding UCOF values of pigs walking a straight line in fouled floor condition. As UCOF increased and available friction from the fouled floor surface decreased, this resulted in higher forward and backward slip frequencies in both limbs for pigs walking in a curve.

The moderate curve design in this study revealed that if pigs are provoked to walk on a fouled floor, pig adaption to floor condition is not enough to ensure walking safety. To obtain more precise design criteria for floors in pig houses, further research is needed to identify when slips actually occur and to relate the biomechanics of this to slip resistance measurements and to required movements of pigs in a pen situation.

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