

Biomechanical gait analysis of pigs walking on solid concrete floor

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Inappropriate floors in pig pens and slippery floor conditions may cause leg problems that reduce animal welfare. Therefore the objectives of the present study were to characterise the walk of pigs on dry concrete solid floor, to evaluate whether pigs modify their gait according to floor condition, and to suggest a coefficient of friction (COF) that ensures safe walking on solid concrete floors for pigs. Kinematic (50 Hz video recordings in the sagittal plane) and kinetic (1 KHz force plate measuring three perpendicular ground reaction forces) data were collected from four strides of both the fore- and hindlimbs of 30 healthy pigs walking on dry, greasy and wet concrete floor with 10 pigs on each floor condition. The COF of the floor conditions were tested in a drag-test. The results from the gait analysis showed that the pigs adapted their gait to potentially slippery floors by lowering their walking speed and reducing their peak utilised COF on greasy and wet (contaminated) floors compared with dry floors. Moreover, the pigs shortened their progression length and prolonged their stance phase duration on greasy floor compared with dry and wet floors. Thus the greasy floor appeared the most slippery condition to the pigs, whereas the wet floor was intermediate to the other two conditions. The pigs walked with a four-beat gait, and the limbs differed biomechanically, as the forelimbs carried more load, received higher peak vertical forces and had longer lasting stance phases than did the hindlimbs. The utilised COF from the gait analysis indicated that a high floor COF (> 0.63) is needed to prevent pigs from slipping and thus to ensure safe walking on dry concrete floors.

Keywords: animal welfare, floor type, friction, gait, pigs

Introduction

In modern intensive pig production leg problems constitute a common welfare problem in pig herds. The term 'leg problems' covers many ailments: locomotion disturbances; leg weakness; joint disorders and claw disorders (Jørgensen, 2003). The prevalence of leg problems is high, thus in Denmark 13% of the slaughter pigs suffer from leg weakness, 19% from joint disorders and 9% from claw disorders (Jørgensen, 2003). Among the adult breeding animals leg weakness caused the death or euthanasia of 29% sows and gilts delivered to a rendering plant (Christensen *et al.*, 1995). Furthermore, in sow herds with a mortality of 10% (Danish average) or higher as many as 72% sows were killed because of leg problems (Kirk *et al.*, 2005).

Leg problems may occur for several reasons, and one of the major environmental factors is the pig pen floor. Floors

with too low friction may cause slips damaging the joints due to overexertion and falls which may cause impact injuries and ultimately can result in fractured legs; hard floors cause bruising and swollen joints from lying on the floor; too abrasive floors cause excessive wear of the claws and skin lesions whereas too little abrasiveness leads to overgrown claws (McKee and Dumelow, 1995). Moreover, slippery floors can potentially make animals adopt abnormal movement patterns, which may have adverse effects on the limbs.

Normal gait and the effect of floor condition have been widely analysed in humans. Thus when anticipating a slippery floor postural and temporal gait adaptations reduced the peak utilised coefficient of friction (COF; Cham and Redfern, 2002), where the utilised COF (μ COF) was defined as the ratio of the shear (the resultant of the anteroposterior and mediolateral horizontal forces) and the vertical GRFs generated by the foot during walk. Furthermore, the peak

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uCOF has been shown to increase with increased walking speed (Powers *et al.*, 2002). In cows the locomotion has been investigated under dry, wet and slurry-covered floor conditions (Phillips and Morris, 2000). Moreover the slips of cows on dry and slurry-covered solid floors have been studied (Albutt *et al.*, 1990), and the uCOF produced by cows performing three different locomotor behaviours have also been examined (Van der Tol *et al.*, 2005). In pigs, however, biomechanical gait analysis and studies of the effects of floor condition on locomotion are sparse despite the high prevalence of leg problems. Thus, one study kinematically analysed the gait of pigs on wet concrete floors with different friction coefficients (Applegate *et al.*, 1988), however no ground reaction forces (GRFs) were measured. Another study measured the GRFs of young pigs walking on sailcloth, for which they only estimated the COF (Webb and Clark, 1981). Hence, it has so far not been studied kinetically whether pigs adapt their gait according to the floor condition. In the present study it is hypothesised that pigs do modify their gait in response to changes in the floor condition.

Pigs are mainly housed on slatted or partly slatted floors however normal gait on solid floor has to be characterised, before the effect of different slatted floors on the gait of pigs can be established. In addition the floor of a pig pen is often wet, dirty or greasy from water, urine and faeces, therefore it is important to examine the floors under similar yet standardised conditions. Furthermore pigs reared under intensive production systems may have limited exercise possibilities caused by the generally small pens and/or high stocking densities. Lack of exercise reduces muscle weight and bone strength in sows (Marchant and Broom, 1996), additionally it reduces bone development in growing pigs (Weiler *et al.*, 2006). Thus the frictional property of the floor in the part of the pig pen meant for feeding, drinking, dunging and moving around (i.e. not the resting area) should not further restrict the pigs from exercising.

Slips occur considerably more often in sows manoeuvring on a smooth metal floor compared with a ridged plastic floor (Leonard *et al.*, 1997) and a rubber mat (Boyle *et al.*, 2000). In these studies the slipperiness of the floors, unfortunately, was not measured. Traditionally the COF is used as an indicator of the slipperiness of a floor. Two frictional measurements are used to characterise floors, namely the static COF (sCOF) and the dynamic COF (dCOF), which can be influenced by the floor condition, i.e. the absence or presence of contaminant fluids. Theoretically, a slip occurs when the uCOF produced during foot-floor contact exceeds the sCOF of the floor. Thus, in cows increasing the sCOF showed a rapid decrease in slipping according to results rearranged by Webb and Nilsson (1983). The present study investigates the uCOF produced by the pigs during walk relative to the sCOF and the dCOF during dry and contaminated floor conditions.

The purposes of this study were to characterise the walk of healthy pigs on concrete solid floor biomechanically, to examine if pigs modify their gait according to the floor

condition, and to suggest a safe COF for solid concrete floors.

Material and methods

Animals

Thirty Duroc × Yorkshire × Landrace (D(YL)) crossbred pigs from 17 different sows were studied. The pigs were either gilts or castrates that were 135 ± 9 days old (range 119 to 150 days). They were housed on partly slatted concrete, and they showed no signs of lameness, i.e. they walked without limping when allowed to walk on solid floor outside their home pen.

All procedures involving animals were approved by the Danish Animal Experiments Inspectorate in accordance with the Danish Ministry of Justice Law no. 382 and Acts 333, 726 and 1016.

Procedures

Prior to the gait analysis some body parameters were measured. Firstly, the pigs were weighed. Secondly, the length of their limbs were measured; the forelimb from the lateral condyle of the humerus to the ground and the hindlimb from the lateral condyle of the femur to the ground, respectively.

The pigs were tested individually on the test floor along a 0.5 m wide and 6 m long aisle. The test floor was solid concrete (flagstone, Perstrup Concrete Industry A/S, Kolind, Denmark), which had a rough and absorbing surface. Dry, wet and greasy floor conditions were tested with three different groups including 10 pigs each, since in the present experiment we wanted the pigs to be free of previous experiences with the test floor. The pigs were assigned randomly to floor condition groups. During wet condition the floor of the entire aisle was wetted with tap water, whereas the greasy condition was obtained with a thin layer of rapeseed oil (Coop X-tra, Coop A/S, Albertslund, Denmark). Kinematic and kinetic data were collected simultaneously from the pigs, as they walked at a self-selected, steady speed.

Kinematics

On the pigs' right side markers were painted on the spinous tuber of the scapula for measuring general walking speed and progression length, and centrally at the most distal edge of the lateral fore- and hindclaws for measuring swing phase duration. A digital video camera (Panasonic NV-DS30EG, Panasonic Denmark, Glostrup, Denmark) recorded the central 1.4 m of the aisle from the right side in the sagittal plane at 50 Hz.

Kinetics

Three GRFs (vertical, anteroposterior and mediolateral horizontal components) were recorded from a $0.20 \times 0.30 \text{ m}^2$ force plate (Bertec Corporation, Columbus, OH). The force plate was mounted invisibly to the pigs in the central part of the aisle with test floor on it. The analog force signals

(range ± 5 V and maximum load 5 kN) were sampled at 1 KHz, A/D-converted using a 16 bit PCI-DAS6035 card (Measurement Computing, Middleboro, MA) and recorded on a personal computer. The resolution of the vertical and horizontal force signals were 0.15 N per bit and 0.08 N per bit, respectively. As a pig stepped on the force plate a light emitting diode (LED) within the camera field, but above the view of the pigs, went on to synchronise kinetic and kinematic data. The force data collection, turning on and off the LED, and turning off the camera was done by custom-made software (SideStepper version 1.3b, TA, Aalborg, Denmark). A successful trial was defined by a pig keeping a steady pace without stopping or running and placing its' forefoot or hindfoot or both feet, but separated in time, entirely on the force plate. Three to four successful trials for both fore- and hindlimb were obtained. The number of times a pig had to walk through the aisle ranged from five to 36 times, which was achieved within maximum 1 hour per pig.

Data processing

The video sequences were digitised using Pinnacle Studio (version 8, Pinnacle Systems, Inc., Mountain View, CA), and two-dimensional coordinates were constructed (by direct linear transformation) and digitally low-pass filtered by a fourth order Butterworth filter with a cut-off frequency of 8 Hz using APAS (Ariel Dynamics Inc, Trabuco Canyon, CA). The cut-off frequency was determined based on a frequency analysis. All gait variables were calculated using MATLAB[®] (2002, The MathWorks Inc, Natick, MA, USA). Moreover, the video sequences were visually inspected for the occurrence of slips.

The kinematic variables calculated were the: walking speed; progression length, i.e. the distance between two consecutive initial ground contacts of the same foot; and swing to stance phase duration ratio (values < 1 signify that swing phase is shorter than stance phase). The kinetic variables calculated from the GRFs were the: stance phase duration; mean vertical force (mean GRF_v); peak vertical force (Peak GRF_v); peak and minimum horizontal anteroposterior forces (peak GRF_{ap} and minimum GRF_{ap}); peak and minimum horizontal mediolateral forces (peak GRF_{ml} and minimum GRF_{ml}). All GRFs were normalised to body weight and therefore expressed in N/kg.

The instantaneous uCOF was calculated throughout the stance phase, which for the uCOF was defined as the part of the stance phase where the GRF_v was above 10% of the peak GRF_v exerted by the limb. The value of 10% was chosen to avoid the very early and late stance phase parts during which spurious maxima occur due to division by small values of vertical forces (Powers *et al.*, 2002). Furthermore, the boundary ensured that at least 5% of the body weight was on the limb, corresponding to the definition by Hanson *et al.* (1999). The number of force data differed between stance phases due to differences in the pigs' walking speed, thus to normalise the lengths of the stance phases, data were smoothed by a cubic spline filter

resulting in 100 equidistant values of uCOF for each stance phase, after which the peak uCOF was found.

Floor friction

The frictions of the concrete floor in dry, greasy and wet conditions were measured (at the Danish Technological Institute[†]) using an Instron 5569 drag device. The drag device had a polyether urethane material (Elastollan[®] 1185A, Elastogran GmbH, Lemförde, Germany) on the measuring surface (area: 0.064×0.064 m²; weight: 5 kg), which was dragged across the test surface. The sCOF was defined as the peak occurring at the onset of movement, and the dCOF was defined as the mean of measurements over a distance of 0.05 to 0.1 m. Ten measurements were made at different places, and the average sCOFs and dCOFs were calculated from these 10 measurements.

Statistical analysis

The kinematic and kinetic variables were tested separately in the following repeated measurement model:

$$Y_{ijkl} = \mu + \text{con}_i + \text{limb}_j + (\text{con} \times \text{limb})_{ij} + \text{SOW}_k \\ + \text{LIMB}(\text{PIG})_l + \varepsilon_{ijkl}$$

where the response variable Y was the gait variable of the $ijkl$ th observation; μ was the overall mean; con_i the systematic effect of floor condition ($i = \text{dry; wet; greasy}$); limb_j was the systematic effect of limb ($j = \text{forelimb; hindlimb}$); SOW_k was the random effect of sow or kinship ($k = 17$); $\text{LIMB}(\text{PIG})_l$ was the random effect of limb within pig ($l = 30$); and ε_{ijkl} was the random residual error term associated with the $ijkl$ th observation. All random terms in the models were considered independent, and data were checked for normality. In a backward elimination procedure the two-way interactions with the largest P -values were removed one at the time, leaving only significant variables in the model. The SAS[®] PROC MIXED procedure was used (2001, Statistical Analysis Systems Institute Inc., Cary, NC) with the Kenward-Roger degree-of-freedom procedure due to unbalanced data as a result of missing observations (Littel *et al.*, 2002). Plotting the residuals against the predicted values fulfilled the homogeneity of variance assumption.

The body parameters were tested separately in a SAS[®] PROC GLM procedure (2001, SAS Institute Inc, Cary, NC) using floor condition as the explanatory variable. The sCOF and dCOF were tested using a paired t-test. A significance level of $P < 0.05$ was used throughout.

Results

Body parameters

The body weights and limb lengths for the pigs from the three floor conditions are reported in Table 1. There were no significant differences between the floor conditions.

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Table 1 The body parameters of the pigs from the three floor conditions (least square means (s.d.), n = 10)

	Floor condition		
	Dry	Greasy	Wet
Body weight (kg)	75.0 (6.0)	74.3 (4.3)	72.4 (5.5)
Length (m)			
Forelimb	0.285 (0.015)	0.295 (0.015)	0.290 (0.010)
Hindlimb	0.360 (0.015)	0.365 (0.015)	0.370 (0.020)

Furthermore, preliminary analyses showed that sex had no effect on any of the gait variables.

Kinematics

The walk of the pigs was a four-beat gait characterised by alternating two- and three-limb support phases. The pigs' walking speed was significantly faster on dry floor compared with greasy and wet conditions. The progression length was significantly longer on dry floor compared with greasy condition, whereas wet condition was intermediate. The stance phase duration was significantly longer on greasy floor compared with dry and wet conditions. Moreover the stance phase duration was significantly longer on the forelimbs compared with the hindlimbs. The swing to stance phase ratio was significantly lower on the forelimbs than on the hindlimbs. The significant effects of floor condition and limb on the gait variables are given in Table 2.

Kinetics

Representative tracings of the three GRFs for the forelimb and the hindlimb of a pig walking on dry floor are shown

in Figure 1. The forelimb GRF_v followed a two-humped pattern with the second maximum being higher than the first maximum, a pattern, which most often was reversed in the hindlimb. In both limbs there was typically a short period during the initial stance phase with minor deflections before the vertical force went into a steady rise.

The time course of the GRF_{ap} was approximately sinusoidal with an initial decline to a negative maximum, when backward forces acted on the foot of the pig, followed by a rise to a positive maximum, when forward forces acted on the foot of the pig. This force component also showed minor deflections during initial stance phase. In addition, the range of the GRF_{ap} was less than half the range of the vertical force. The pattern of the GRF_{ml} was less consistent and very different between limbs, but was negative during most of the stance phase, meaning that the foot of the pig was pushing outward in lateral direction. The range (i.e. the amplitude) of the GRF_{ml} was the smallest of the three GRFs (Figure 1).

The mean GRF_v and peak GRF_v exerted by the forelimbs were significantly higher than the force exerted by the hindlimbs (Table 2). The peak GRF_{ap} was significantly lower on the forelimbs compared with the hindlimbs for the greasy and wet conditions, whereas on dry floor the limbs did not differ significantly, moreover the forelimbs exerted significantly less force on greasy floor compared with the other conditions. The Min GRF_{ap} on dry floor was significantly more negative on the hindlimbs compared with the forelimbs, whereas on greasy and wet the limbs did not differ significantly. As for the peak GRF_{ml} the hindlimbs exerted significantly higher force than the forelimbs, moreover the hindlimb forces were significantly higher on

Table 2 The significant effects of floor condition and limb on the gait variables (least square means (s.e.))[†]

	n	Floor condition			Significance	Limb		Significance
		Dry	Wet	Greasy		Fore	Hind	
Kinematics								
Walking speed (m/s)	192	0.88 (0.03) ^a	0.79 (0.03) ^b	0.74 (0.03) ^b	**			
Progression length (m)	192	0.75 (0.01) ^a	0.73 (0.01) ^{ab}	0.70 (0.01) ^b	**			
Swing/stance phase ratio	192					0.62 (0.02) ^a	0.70 (0.02) ^b	***
Stance phase duration (s)	226	0.60 (0.02) ^a	0.63 (0.02) ^a	0.69 (0.02) ^b	**	0.69 (0.02) ^a	0.59 (0.02) ^b	***
Kinetics								
Mean GRF _v (N/kg)	226					3.76 (0.04) ^a	3.22 (0.04) ^b	***
Peak GRF _v (N/kg)	233					5.63 (0.06) ^a	4.43 (0.06) ^b	***
Peak GRF _{ap} (N/kg)	227	F 0.80 (0.04) ^{bc}	0.72 (0.04) ^b	0.61 (0.04) ^a	***			
		H 0.76 (0.04) ^b	0.87 (0.04) ^c	0.75 (0.04) ^b				
Min GRF _{ap} (N/kg)	227	F -0.75 (0.04) ^b	-0.77 (0.04) ^{ab}	-0.78 (0.04) ^{ab}	*			
		H -0.87 (0.04) ^a	-0.72 (0.04) ^b	-0.71 (0.04) ^b				
Peak GRF _{ml} (N/kg)	227	F 0.07 (0.01) ^a	0.05 (0.01) ^a	0.06 (0.01) ^a	**			
		H 0.20 (0.01) ^b	0.14 (0.01) ^c	0.12 (0.01) ^c				
Min GRF _{ml} (N/kg)	227					-0.59 (0.02) ^a	-0.29 (0.02) ^b	**
Utilised COF								
Peak uCOF	224	0.48 (0.02) ^a	0.42 (0.02) ^b	0.32 (0.02) ^c	***			

^{a,b,c} Different superscripts denote significant differences *0.01 < P < 0.05; **0.001 < P < 0.01; ***P < 0.001.

[†] F = forelimb; H = hindlimb; GRF = ground reaction force; v = vertical; ap = anteroposterior horizontal; ml = mediolateral horizontal; uCOF = utilized coefficient of friction. In case of interaction between floor condition and limb, the limbs are reported separately for each condition.

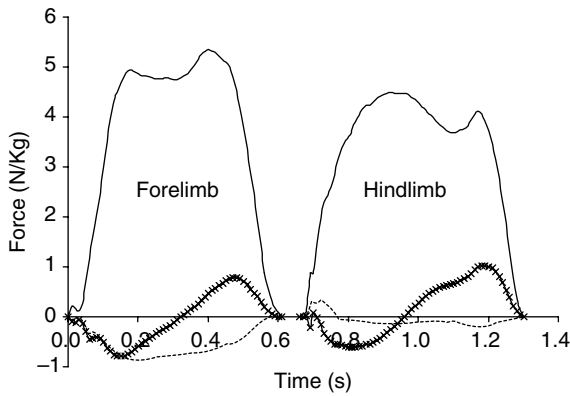


Figure 1 A typical example of the vertical (GRF_v; full line), anteroposterior horizontal (GRF_{ap}; crosses) and mediolateral horizontal (GRF_{ml}; dotted line) ground reaction forces exerted by the forelimb (left curves) followed by the hindlimb (right curves) of a pig walking on a dry floor.

dry floor compared with greasy and wet conditions. The min GRF_{ml} was significantly more negative in the forelimbs compared with the hindlimbs.

Utilised COF

The average uCOF for the fore- and the hindlimbs are shown for the three floor conditions in Figure 2. For both limbs the uCOF was highest at the beginning and towards the end of the stance phase with a minimum around mid stance. Deviations from the dry condition were largest during initial and final stance phase during which the uCOF of the greasy and wet conditions were lower than that of the dry condition. Moreover, the visual inspection of the video sequences revealed slips in 1% of the steps on dry floor (one slip out of 77 steps), 11% on wet floor (eight out of 76) and 13% on greasy floor (nine out of 67).

The frequency distributions of the peak uCOFs for the pigs on the three floor conditions are shown in Figure 3. Looking at all three floor conditions the peak uCOF ranged from 0.18 to 0.82, however on greasy floor the highest peak uCOF measured was only 0.59 (Figure 3). The mean peak uCOF was significantly lower on greasy floor compared with wet floor, which again was significantly lower compared with dry floor (Table 2). The 99% confidence limit of the peak uCOF for dry floor (*n* = 10) was 0.63,

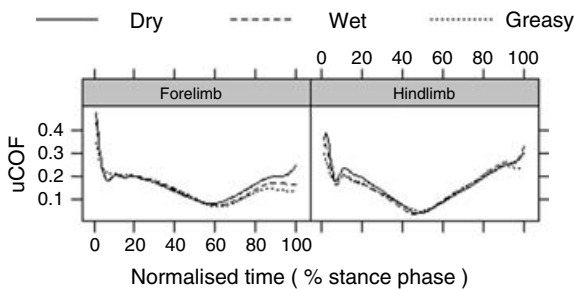


Figure 2 The average uCOF (dimensionless) of the forelimb (left part of figure) and the hindlimb (right part) of pigs walking on dry, wet and greasy floor conditions.

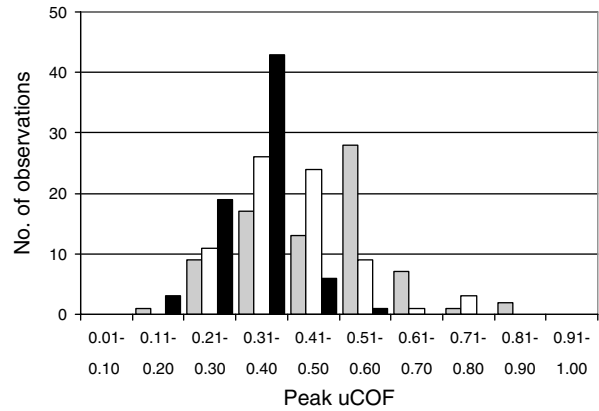


Figure 3 The frequency distribution of the peak uCOF (dimensionless) of pigs walking on dry (grey bars), wet (white bars) and greasy (black bars) floor conditions (*n* = 224).

calculated according to formula 1:

$$99\% \text{ confidence limit} = \text{average uCOF} + (2.58 \times \text{s.d.}) \tag{1}$$

in which the s.d. was calculated from the s.e. and *n* (Table 2) according to formula 2:

$$\text{s.d.} = \text{s.e.} \times \sqrt{n} \tag{2}$$

Floor friction

In general the dynamic COFs were lower than the static COFs, and the sCOF was highest on the dry floor (Table 3). However, only the dCOF of the greasy floor was significantly lower than the dCOFs of the dry and wet floors and all three sCOFs (*P* < 0.001). The lowest COF (greasy floor dCOF) was higher than the average uCOF during the entire stance phase (Figure 2), however as the Peak uCOF ranged up to 0.82, both the sCOFs and dCOFs were exceeded in several steps.

Discussion

The main finding of this study confirmed the hypothesis that pigs adapt their walk to potentially slippery surfaces. The pigs reacted to the greasy and wet (i.e. contaminated) floors by lowering their walking speed and peak uCOF. Moreover, the pigs reduced their progression length and increased their stance phase duration on greasy floor compared with dry floor. Furthermore, the forelimbs and hindlimbs of the pigs differed biomechanically, as the forelimbs received higher peak vertical forces as well as higher mean vertical forces than did the hindlimbs. The body weight and limb length of the pigs were similar for all floor conditions (Table 1), thus the effects of floor condition were not caused by different body sizes.

The pigs reduced their walking speed by 16% and their progression length by 7% from dry to greasy floor, and simultaneously the pigs prolonged the stance phase by

Table 3 The static and dynamic COFs of the three floor conditions (means (s.d.) and ranges, n = 10)

	Dry		Wet		Greasy	
	sCOF	dCOF	sCOF	dCOF	sCOF	dCOF
Mean	0.67 (0.06) ^a	0.65 (0.05) ^a	0.64 (0.03) ^a	0.63 (0.03) ^a	0.64 (0.03) ^a	0.51 (0.02) ^b
Range	0.57–0.77	0.59–0.73	0.58–0.68	0.57–0.66	0.59–0.69	0.47–0.54

^{a,b} Different superscripts denote significant differences ($P < 0.05$).

15%. The reduced speed and progression length of the pigs on greasy floor was in agreement with a study on cows, which walked slowest and took shortest steps on the floor with the lowest friction (Telezhenko and Bergsten, 2005). Correspondingly, cows walked more slowly on a floor contaminated by slurry compared with dry floor (Phillips and Morris, 2000). Moreover the increased number of slips on the contaminated floors by the pigs in the present study was in accordance with the finding of more slips on slurry-covered than on dry concrete floor in walking cows (Albutt *et al.*, 1990).

The relative mean GRF_v showed 54% of the body weight to be carried by the pigs' forelimbs, thus reflecting that the centre of gravity was relatively closer to the forelimbs. This uneven weight distribution in the pigs was similar to the one found in cows (Webb and Clark, 1981). Thus, leg problems owing to high loads and impacts should be expected to occur more frequently in the forelimbs compared with the hindlimbs, as supported by the work of Jørgensen *et al.* (1995). The peak GRF_v of the pigs walking at ~ 0.8 m/s was unevenly distributed with 56% of the load received by the forelimbs. The magnitude of these peak loads were comparable to those found in dogs of approximately 30 kg and walking at 1 m/s (Roush and McLaughlin Jr, 1994), but not to those experienced by a cow of 630 kg (Van der Tol *et al.*, 2005) or humans weighing 69 kg on average (Cham and Redfern, 2002). The latter differences may be attributed to different walking speeds in these studies.

The lowered peak uCOF on the contaminated floors in the present study showed that the pigs adapted their gait in a way that minimised their risk of slipping on a potentially slippery surface, whereas pigs on dry floor produced a high Peak uCOF by walking more confidently. Thus the pigs reduced their peak uCOF by 33% from dry to greasy condition and from dry to wet condition by 12%, which was very similar to the reduction in the uCOF produced by humans anticipating slippery floors (Cham and Redfern, 2002). Part of the explanation for the reduced peak uCOF was the pigs' lowered speed when walking on contaminated floors, which was supported by the finding of others that the uCOF is positively correlated with walking speed (Powers *et al.*, 2002). In cows, the uCOF was 0.54 when walking straight and 0.83 in single cases of a cow walking a curved path (Van der Tol *et al.*, 2005). In humans the uCOF was around 0.30 on a high friction surface (Kulakowski *et al.*, 1989). Further, a value of 0.23 for

different groups of people at level walking was reported (Burnfield *et al.*, 2005). Therefore, in comparison with other species pigs walking on a dry floor utilised the frictional floor property to a greater extent than humans but slightly less than cows.

In the present study the 99% confidence limit of the uCOF on the dry floor was 0.63, and one slip out of a total of 77 steps was registered on the dry floor by visual inspection. Assuming that the pigs on dry floor walked normally, whereas the lowered peak uCOF on the contaminated floors was an expression of restricted gait, then the 0.63 can be considered as a COF threshold, which ensures safe walking on a dry concrete surface. This threshold is considerably higher than the differing recommendations, which have been suggested for the minimum COF of floors for animal housing and human walk ways i.e. a dCOF of 0.35 for group-housed slaughter pigs on solid floors was suggested (Bähr and Türpitz, 1976) and has been supported by others (Kovacs and Beer, 1979; Nilsson, 1988). Moreover, a COF of 0.4 to 0.5 was recommended, because cows walked slower, made longer strides and had larger range of motion when the sCOF of the floor increased (Phillips and Morris, 2001). In a study of walking humans some individuals exceeded the threshold recommendation of sCOF > 0.5 which several North American states give to ensure safe floors (Burnfield *et al.*, 2005). Moreover, comparing the uCOF from the gait analysis of the present study with the greasy floor dCOF indicated that a high dCOF, higher than the 0.51 tested, is needed to ensure pigs safe walking on contaminated concrete floors. However, although a high COF might give a good walking surface this may not be suitable for lying, as the abrasiveness may cause skin lesions (Boyle *et al.*, 2000), thus high-friction surfaces should not be used in the resting area of the pig pen, moreover additional work should investigate the long-term effects of housing pigs on a high-friction surface.

The propulsion/braking patterns, expressed by the peak GRF_{ap} and min GRF_{ap} respectively, showed that mainly braking occurred during the first half, and propulsion during the last half of the stance phase for both the fore- and hindlimbs of the pigs. However, small disturbances happened during the first 0.04 s after foot impact. These disturbances have also been found in sheep and dogs and have been attributed to the high forward velocity of the foot during impact (Jayes and Alexander, 1978). Compared with dry condition the contaminated floors caused large differences in peak braking force between the limbs of the

pigs, suggesting that braking was equally divided between the limbs on dry floor, but decreased on the forelimbs, and thus shifted braking to the hindlimbs on contaminated floors. Propulsion on dry floor was largest on the hindlimbs, whereas on greasy and wet floors propulsion was equally divided between fore- and hindlimbs. The movements made to stabilise the travel direction, expressed by the peak and min GRF_{mlr}, showed that in the pigs the hindlimbs made inward corrections two to three times greater than the forelimbs with the difference being most pronounced on dry floor, suggesting that contaminated conditions restricted the medially directed stabilising movements.

The alternating two and three limb support phase pattern displayed by the pigs in the present study was comparable to the walk described for dogs (Hottinger *et al.*, 1996), dogs and sheep (Jayes and Alexander, 1978), dairy cows (Flower *et al.*, 2005) and horses (Hodson *et al.*, 2001). The stance phase of the hindlimbs was 14% shorter compared with the stance phase of the forelimbs. This was also reflected in the swing/stance phase ratio being 11% higher in the hindlimbs, thus confirming the findings in pigs half the weight (Applegate *et al.*, 1988) of the ones in the present study.

Sex had no influence on any of the measured variables in the present study, although in slaughter pigs of about 105 kg the sex affects some leg problems (Jørgensen, 2003), therefore when studying D(YL) pigs at 75 kg, gilts and castrates were comparable. This was in agreement with another study using castrates males and female slaughter pigs (Jørgensen, 1994) and can probably be ascribed to a combination of the young age and the use of castrated males in the present study.

Healthy pigs with no signs of lameness were used in this non-invasive study. Furthermore, the pigs walking on wet or greasy floors were not subjected to a floor condition more extreme than what animals in normal intensive pig production may experience. Moreover, the present study will potentially benefit the welfare of many pigs by highlighting the importance of the physical floor properties in pig pens and their interactions with the animals, as called for by Webb and Nilsson (1983).

In conclusion, the pigs adapted their gait according to floor condition to avoid slipping on contaminated and potentially slippery floors compared with dry floor. The pigs compensated by lowering their walking speed and their peak uCOF. Moreover, the pigs' progression length was shortened and stance phase duration prolonged only on greasy floor, thus greasy floor appeared the most slippery condition to the pigs, whereas wet floor was intermediate. The pigs walked with a four-beat gait during which the fore- and hindlimbs differed biomechanically, as the forelimbs carried 54% of the body weight and received peak forces corresponding to 56% the body weight. The uCOF from the gait analysis indicated that a high floor sCOF (>0.63) is needed to prevent pigs from slipping and thus ensure safe walking on dry concrete floors. Moreover,

comparing the uCOF from the gait analysis with the greasy floor dCOF indicated that a high dCOF is important to ensure pigs safe walking on contaminated concrete floors. Future studies should further elucidate the effect of floor condition by quantifying the slip distances on different floor conditions and by investigating further biomechanical measures like foot velocities and joint moments, which may play important roles in joint loading.

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