Gait and Force Analysis of Provoked Pig Gait on Clean and Fouled Rubber Mat Surfaces

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Abstract

Materials that increase floor friction forces in absorption of foot pressure could reduce the risk of slipping, i.e. promote walking safety. The effects of fouled rubber mat 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 condition through reduced walking speed (10%), prolonged swing and stance time and a higher number of 3-limb support phases, but kept stride length and diagonality constant. This adaption produced a threefold reduction in lateral horizontal forces and kept braking and propulsion forces constant, resulting in a constant peak utilised coefficient of friction (UCOF) level in fore limbs but a 31% reduction in UCOF in hind limbs.

The better traction for pigs walking on rubber matting compared with concrete is due to a more effective transmission of forces from the limb to the elastomer, dissipating the forces into energy within the material, and thus impeding the effect of centripetal force, with less displacement of body centre of gravity and less forward and backward slip. Pig forward slip frequency on fouled rubber matting was 65 and 51% lower for fore and hind limbs respectively compared with pigs walking a curve on fouled concrete.

The soft flooring material improved gait adaption and could thus improve walking safety.

Keywords: pig, floor, friction, slip, rubber mat, kinematics, kinetics.

Nomenclature

BPN	British Pendulum Number represents the frictional property measured by SRT.
COF	Coefficient of friction; ratio between frictional and normal force, F_{μ}/F_{N}.
CW_c	Pigs walking a curved test aisle on concrete floor.
CW_r	Pigs walking a curved test aisle on rubber mat flooring.
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	Diagonal sequence walk 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 other.
Elastomer	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	Force (N) depending 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}. GRF_v Vertical GRF GRF_{long} Longitudinal GRF (in the travelling direction) 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 other.
Slip safe	An environment where the measured DCOF is greater than the peak UCOF.
SRT	Slip Resistance Tester, a dynamic pendulum impact-type 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).
Stride time	Time interval (s) between two consecutive foot strikes of the same foot.
Swing time	Time (s) the foot is not in contact with the ground.
Symmetrical gait	Gait 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

For reasons of technical design and economy, flooring and flooring systems in animal houses are often made from hard materials, which means that they do not deform under the pressure of an animal foot. In contrast, pasture ground is deformable by foot pressure (Hernandez-Mendo et al., 2007).

Recent studies of rubber walkways in cubicle barns have confirmed the benefits for cow locomotion (Boyle et al., 2007; Flower et al., 2007; Telezhenko et al., 2007; Reubold, 2008).

Reubold (2008) showed in a study of six different rubber walkway covers that the degree of compressibility of rubber walkway cover was well adapted for walkway evaluation. A deformation of 1.4 mm gave good slip resistance and reduced claw lesions.

Studies on foot and leg injuries in pig husbandry systems (Jørgensen 2003; Lahrmann et al., 2003) have focused on identifying the cause of the problem. Gait and force analysis has proven to be a useful method in linking claw injuries to surface material conditions in cows (Flower et al., 2005; van der Tol et al., 2005) and pigs (Applegate et al., 1988; Thorup et al., 2007; von Wachenfelt et al., 2008).

Floor properties such as surface coefficient of friction (COF), abrasiveness and softness (Webb & Nilsson, 1983; Nilsson, 1988), and their interactions with the pig claw (Webb & Nilsson, 1983; Webb, 1984; Applegate et al., 1988; Thorup et al., 2007) are among the key factors in understanding the causes of slip and fall accidents (Redfern & DiPasquale, 1997; Hanson et al., 1999).

The foot forces that are generated when a foot comes in contact with the ground require friction to prevent slip (Hanson et al., 1999). In pig gait, the COF depends on claw properties, flooring and floor conditions (e.g. dry, wet or manure-fouled).

A material that increases floor friction forces at toe-on and toe-off in absorption of foot pressure could reduce the horizontal forces at impact and thereby also reduce the risk of slipping, i.e. increase walking safety (Nilsson, 1988; van der Tol et al., 2005).

Hanson et al. (1999) reasoned that to make the environment slip-safe, it needs to be designed so that the probability of slip and fall is extremely low, i.e. with the difference between the measured DCOF and peak UCOF greater than zero. However, the probability of slip is determined not only by the shoe/foot, floor and presence of contaminants, but also by the types of movements required, i.e. fast or slow (Hanson et al., 1999).

The objectives of the present study were to characterise provoked pig gait (walking a curve) on a clean rubber mat surface and to evaluate the effect of surface fouling on pig gait by use of kinematics and kinetics. A previous study showed that on hard flooring, pigs adapted to the floor surface but had a high slip frequency in fouled floor condition (von Wachenfelt et al., 2009b). The hypothesis of the present study was that pigs would adapt their gait to the softer floor when walking a curve, and that the softer flooring would improve walking safety compared with hard flooring materials.

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, the claws were examined according to a standard procedure (Brooks et al., 1977). The average animal weight during the test period (4 d) was 98 kg (SD = 18 kg). The subject pigs and the test procedures were described by von Wachenfelt et al. (2008, 2009a).

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 20 mm thick rubber matting (KEN® Gummiwek Kraiburg Elastik, Germany) with a rubber-studded underside profile. The elasticity of the matting, measured as deformation under the pressure of a calotte (r = 120 mm), was 1.5, 5.0, and 8.0 mm for 13.5, 26.5, 34.3 Ncm^{-2} (the test was conducted by the German Agricultural Society (DLG)). Pig gait on the test aisle was recorded by a built-in force plate (FP; L 600 x B 900 mm) 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 rubber flooring material. Two floor 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 sampled at 1 kHz.

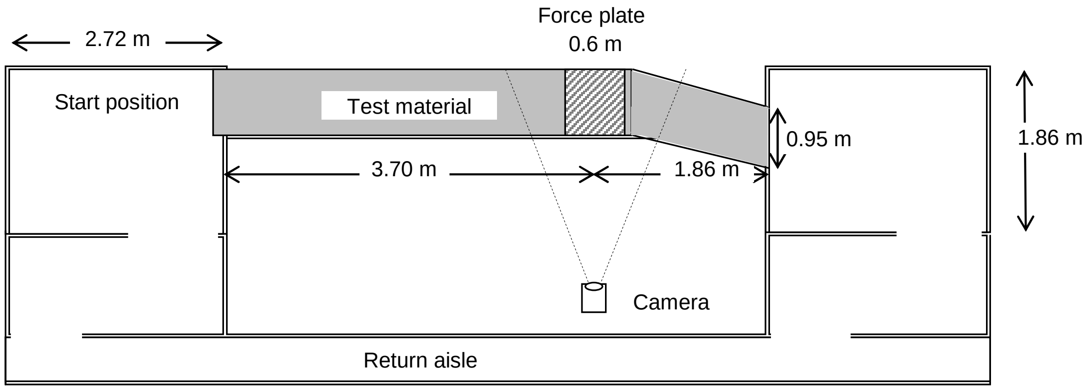

Fig. 1. Plan of the test area.

2.3 Experiment

The pigs walked the test aisle individually at a self-determined 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 1.7% of the passages in clean floor condition and 5.8% of those in fouled condition were unsuccessful and were replaced by new passages. The average time to complete the 10 passages was 14 minutes per pig. The indoor temperature was 17 ± 4°C and the relative humidity 55 ± 17%.

Five positions of the animal were digitised in each DV frame: 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 are described in the nomenclature section. The FP recorded three ground reaction forces (GRF) 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. (2009a).

Two friction test devices, a horizontal pull slip meter (PSM) and a dynamic pendulum impact-type tester (SRT) (ASTM, 1993) were used to record coefficient of friction (COF) and British Pendulum Number (BPN) of the flooring (von Wachenfelt et al., 2009a). 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).

2.5 Data processing

The definition and processing of stride, force and friction data were conducted as described by von Wachenfelt et al. (2008, 2009a). The precondition for stride data calculation was a full stride (which includes a stance phase when the limb is in contact with the ground and a swing phase when the limb is not in contact with the ground (Clayton, 1997)) from each passage. 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 disregarded, whereas a slip above 10 mm was characterised as a slip from which the subject recovered or did not recover from (Applegate et al., 1988; Cham & Redfern, 2002b). No slips occurred from which the pigs fell and did not recover, i.e. could not continue the walk.

2.6 Statistics

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

3. Results

3.1 Gait differences due to surface conditions in walking in a curve

All data were normally distributed. With a curve walking speed of 1.18 ms^{-1} in clean floor conditions and 1.06 ms^{-1} in fouled floor conditions, the walk of pigs walking a curve on rubber mat flooring (CWr) was characterised by a four-beat symmetrical gait distinguished by alternating 2- or 3-limb support phases. Single or 4-limb support phases comprised less than 7 and 1% of observations, respectively. The number of 2-limb support phases decreased from 81 to 70% in fouled floor conditions compared with clean, while the diagonality remained constant and the number of 3-limb support phases increased from 11 to 23%. A gait pattern of a clear diagonal-sequence (DS) walk in clean floor conditions was also maintained in fouled floor conditions (Fig. 2).

For pigs in fouled floor conditions compared with clean, swing and stance time increased by 10% and number of 3-limb support by two-fold. The effects of floor condition on pig gait parameters are given in Table 1.

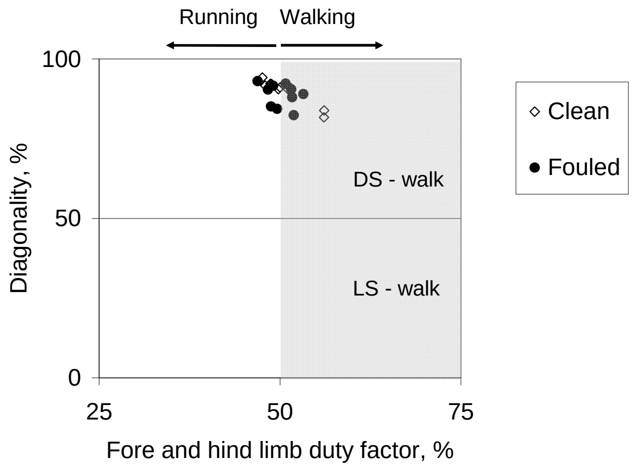

Fig. 2. Hildebrand diagram of diagonality against mean duty factor for symmetrical gaits of 10 pigs walking in a curve on rubber. Open squares represent gait cycles on clean test aisle; solid circles represent cycles on fouled test aisle. The lower right area of the diagram represents LS walking gaits and the upper right area DS walking gaits, adapted from Lemelin et al. (2003).

Table 1. Stride characteristics of 10 provoked pigs walking a curve in clean and fouled rubber floor conditions. Comparison between fore and hind limbs and between conditions (number of samples (n), mean and standard deviation (SD)).

Parameter	Conditions					Limb[2]				
	Clean		Fouled			Fore		Hind		
	n	Mean (SD)	n	Mean (SD)	p[1]	n	Mean (SD)	n	Mean (SD)	p[1]
Walking speed, ms^{-1}	467	1.18 (0.14)	475	1.06 (0.11)	*					
Stride length, m	467	0.94 (0.08)	475	0.92 (0.06)	ns					
Stride time, s	467	0.82 (0.08)	475	0.88 (0.06)	*					
Stride speed, ms^{-1}	467	1.19 (0.11)	475	1.07 (0.10)	*					
Swing time, s	467	0.40 (0.02)	475	0.44 (0.03)	***					
Swing/stance time ratio	476	0.97 (0.12)	468	0.99 (0.10)	ns	472	1.01 (0.09)	472	0.95 (0.12)	*
Stance time, s	467	0.41 (0.05)	475	0.45 (0.05)	*	472	0.43 (0.05)	472	0.44 (0.06)	*
Max stride elevation, m	472	0.06 (0.01)	456	0.07 (0.02)	ns	464	0.07 (0.02)	464	0.06 (0.01)	ns
No. of 1-limb support phases	118	7.23 (2.60)	114	7.24 (2.26)	ns					
No. of 2-limb support phases	118	80.74 (4.96)	114	69.99 (5.67)	**					
No. of 3-limb support phases	118	11.29 (6.20)	114	22.51 (6.81)	**					
No. of 4-limb support phases	118	0.03 (0.11)	114	1.05 (1.64)	ns					
Symmetry, %	118	51.18 (1.06)	114	50.37 (1.27)	ns					
Diagonality, %	118	89.89 (3.93)	114	88.67 (3.64)	ns					
Duty factor, %	467	50.75 (0.03)	475	50.17 (0.02)	ns					

1) Probability limits for evaluating statistical significance: ns= non significant; * = $p<0.05$; ** = $p<0.01$; *** = $p<0.001$
2) Fore and hind limbs in clean and fouled conditions

Vertical and resultant horizontal GRF's for fore and hind limbs from the mean of 10 curve walking pigs on clean and fouled concrete are illustrated in Fig. 3. The mean and peak GRF_v applied decreased by 10 and 20% for fore and hind limbs, respectively, in fouled floor condition, while time of peak GRF_v for fore limbs occurred at 58% stance time compared with 56% for clean conditions. The hind limbs used mid-stance for full vertical force in clean floor conditions, but in fouled floor conditions the hind limbs applied full force earlier at 45% of stance time (Table 2).

The minimum GRF_{long} (braking force) and the peak GRF_{long} (propulsion force) were constant in both limbs and both floor conditions. The minimum GRF_{lat} (outward correction force) showed a significant reduction for fore (52%) and hind (46%) limbs in fouled floor conditions compared with clean, together with a 50% reduction in peak GRF_{lat} (inward correction force) for fore limbs and a 24% reduction in peak UCOF for hind limbs in fouled floor conditions (Fig. 4).

Table 2. Force characteristics of 10 provoked pigs walking a curve in clean and fouled rubber floor conditions. Comparison between fore (F) and hind (H) limbs and between material conditions (number of samples (n), mean and standard deviation (SD)).

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	138	5.83 (0.36)	***	149	4.79 (0.46)	***	***
	H	136	3.90 (0.33)		172	3.71 (0.26)		ns
Peak GRF_v (Nkg^{-1})[1]	F	138	9.84 (0.71)	***	149	7.91 (0.99)	***	***
	H	136	6.26 (0.85)		172	5.52 (0.58)		*
Timing of peak GRF_v (s)	F	138	0.15 (0.03)	*	149	0.21 (0.04)	***	***
	H	136	0.14 (0.02)		172	0.15 (0.03)		ns
Peak GRF_{long} (Nkg^{-1})[1]	F	138	0.26 (0.13)	***	149	0.33 (0.14)	***	ns
	H	136	0.60 (0.17)		172	0.52 (0.12)		ns
Min GRF_{long} (Nkg^{-1})[1]	F	138	-0.72 (0.09)	***	149	-0.79 (0.13)	***	ns
	H	136	-0.57 (0.11)		172	-0.57 (0.06)		ns
Peak GRF_{lat} (Nkg^{-1})[1]	F	138	0.12 (0.03)	***	149	0.06 (0.03)	ns	***
	H	136	0.06 (0.04)		172	0.06 (0.04)		ns
Min GRF_{lat} (Nkg^{-1})[1]	F	138	-0.46 (0.19)	**	149	-0.22 (0.12)	*	**
	H	136	-0.24 (0.07)		172	-0.13 (0.03)		***
Peak UCOF	F	138	0.46 (0.11)	*	149	0.55 (0.20)	ns	ns
	H	136	0.58 (0.10)		172	0.44 (0.12)		**

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

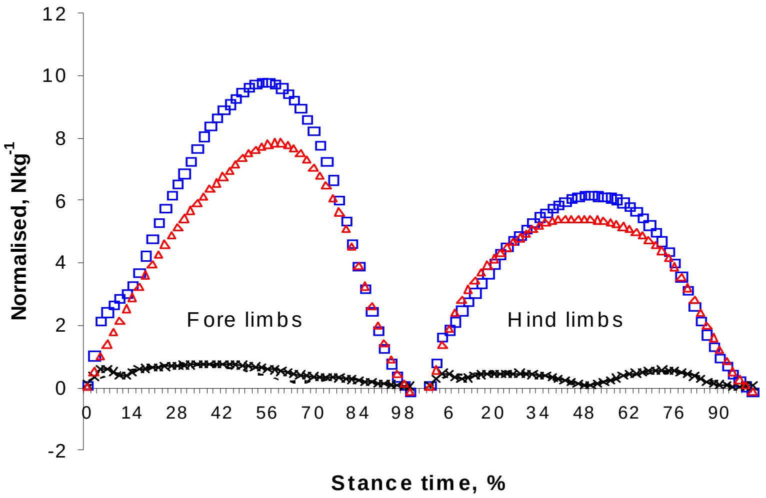

Fig. 3. Vertical and resultant horizontal GRF's for fore and hind limbs from the mean of 10 pigs walking in a curve on clean and fouled rubber mat. The squares represent the vertical GRF on clean rubber mat, cross on line the resulting horizontal GRF on clean rubber mat, triangles the vertical GRF on fouled rubber mat and dotted line the resulting horizontal GRF on fouled rubber mat.

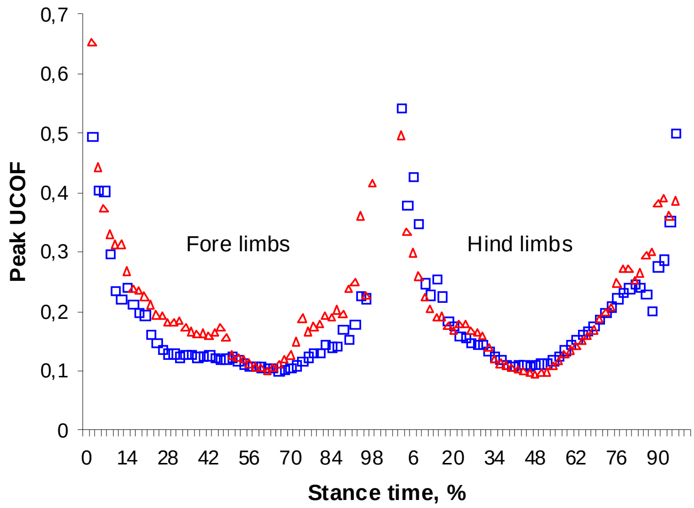

Fig. 4. Peak UCOF values for fore and hind limbs from the mean of 10 pigs walking in a curve on clean and fouled rubber mat. The squares represent pigs walking a curve on clean rubber mat and the triangles represent pigs walking a curve on fouled rubber mat. Values at the very start and end of the stance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

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

Pig fore limbs showed significantly higher swing/stance time ratio and lower stance time than hind limbs but consistent maximum stride elevation in the two types of floor conditions (Table 1). The mean and peak GRF_v applied were 39 and 50% higher for fore limbs than for hind limbs, respectively, in both floor conditions, while the time of peak GRF_v during stance occurred earlier for hind limbs than for fore limbs in both floor conditions (Table 2).

Table 3. Coefficients of static friction (SCOF), dynamic friction (DCOF) and skid resistance (BPN) for rubber floorings tested in laboratory and pig house experiments (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; Rel. humidity % Mean
Clean							
PSM-leather[1]	1.01 (0.02)	***	0.96 (0.01)	***			19.4 ± 0.2; 32
SRT-leather[2]					64.1 (0.03)	***	16.7 ± 3.3; 54
SRT-rubber					90.3 (0.03)	***	20.4 ± 0.4; 67
Fouled							
PSM-leather	0.65 (0.04)		0.53 (0.03)				19.4 ± 0.2; 32
SRT-leather					44.1 (0.05)		16.7 ± 3.3; 54
SRT-rubber					50.5 (0.05)		20.4 ± 0.4; 67

1) PSM-leather = pull slip meter with leather test body
2) SRT-leather = dynamic pendulum impact-type tester with leather test body
3) Laboratory experiment,
4) Pig house experiment
5) Significance level comparing material conditions: * = p<0.05; ** = p<0.01; *** = p<0.001; ns= non significant

The propulsion force was 43 and 63% lower for fore limbs than for hind limbs in clean and fouled floor conditions, respectively. In fouled floor conditions the inward correction force of fore limbs was double that of hind limbs. In clean floor conditions, fore limbs utilised 26% more braking force than hind limbs, whereas in fouled floor condition this difference in braking force increased to 39%. The outward correction force applied by fore limbs was 1.9-fold and 1.7-fold higher than that of hind limbs in clean and fouled floor conditions, respectively. Regarding peak UCOF, the fore limbs utilised 21% less than hind limbs in clean floor conditions, but there was no difference between fore and hind limbs in fouled 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. In general, backward slip time, length and frequency were higher for hind limbs and forward slip time and frequency were higher for fore limbs. Backward and forward slip lengths were of the same order of magnitude. However, compared with forward slip frequency, backward slip frequency was 36% lower for fore limbs and 63% higher for hind limbs (Fig. 5, Table 4). In clean floor conditions no slips > 10 mm were observed.

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

Parameter	Walking a curve on fouled concrete[2]				Walking a curve on fouled rubber			
	n	Limb	Mean (SD)	p[1]	n	Mean (SD)	p[1]	p[1]
Backward slip time, s	234	F	0.06 (0.05)	**	238	0.03 (0.03)	**	*
	234	H	0.14 (0.06)		238	0.08 (0.07)		***
Backward slip length, m	234	F	-0.02 (0.01)	*	238	-0.02 (0.01)	***	ns
	234	H	-0.04 (0.03)		238	-0.03 (0.02)		ns
Backward slip frequency, %	234	F	30.01 (18.80)	***	238	31.83 (14.84)	**	ns
	234	H	45.21 (19.85)		238	46.72 (20.01)		ns
Forward slip time, s	234	F	0.22 (0.09)	***	238	0.18 (0.07)	*	*
	234	H	0.15 (0.09)		238	0.12 (0.09)		ns
Forward slip length, m	234	F	0.09 (0.05)	*	238	0.09 (0.05)	ns	ns
	234	H	0.05 (0.05)		238	0.06 (0.06)		ns
Forward slip frequency, %	234	F	82.14 (25.86)	***	238	49.84 (20.74)	***	**
	234	H	43.09 (17.83)		238	28.63 (16.80)		**

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

2) Data published in von Wachenfelt et al., 2009b

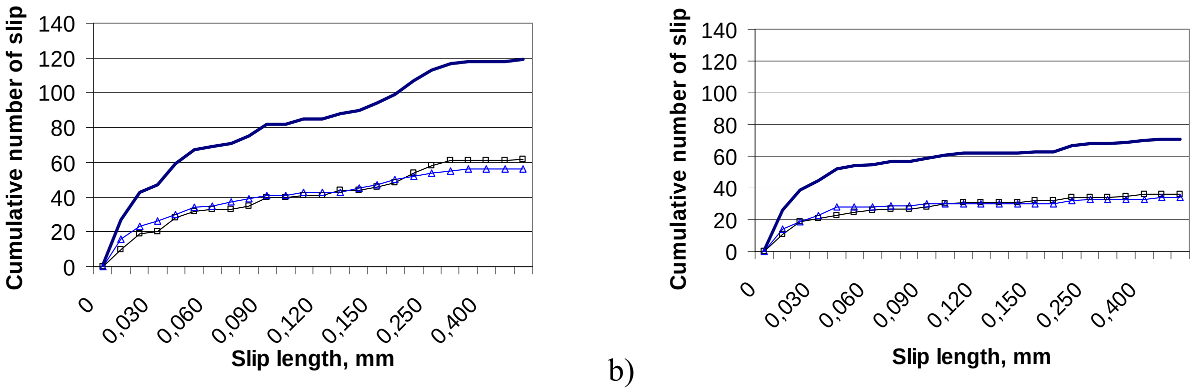

Fig. 5. Number of slips for 10 pigs walking a curve (30° to the right) in fouled rubber floor conditions, a) fore limbs, 118 slips >10 mm in 238 passages on the test aisle, b) hind limbs, 70 slips > 10 mm in 238 passages on the test aisle. In the figures the solid line represent cumulative number of slips, squares left fore or hind limb, triangles right fore or hind limb.

4. Discussion

The mean body weight of the pigs remained constant during the test period, which means that the differences in gait were not caused by differences in body size.

4.1 Main findings

The main finding in this study was that the soft flooring material facilitated the gait adaption and could thus improve walking safety in fouled floor condition. A moderate gait adaption was applied in fouled floor condition through reduced walking speed, prolonged swing and stance time and a higher number of 3-limb support phases, but stride length and diagonality were kept constant. This adaption produced a threefold reduction in lateral horizontal forces and kept braking and propulsion forces constant, resulting in a consistent peak UCOF level in fore limbs but a 31% reduction in UCOF in hind limbs in fouled floor condition. The better traction of rubber matting resulted in less displacement of body centre of gravity and less forward and backward slip.

4.2 Kinematics

4.2.1 Gait differences due to floor conditions

The symmetrical walking pattern with alternating 2- and 3-limb support phases exhibited by the pigs in the present study was similar to that reported for pigs (Thorup et al., 2007; von Wachenfelt et al., 2008).

In both clean and fouled floor conditions, the pigs used a clear DS walk in which the hind foot touched down slightly after the contra-lateral foot. In clean floor condition, CWr pigs had a cautious but confident walk, with a walking speed of 1.18 ms^{-1}. The CWr pigs applied a moderate walking pattern with lower walking speed, longer swing and stance time compared with straight forward walking pigs (von Wachenfelt et al., 2008) in both floor conditions.

The CWr pigs adapted to fouled floor condition through reduced walking speed (10%), lower number of 2-limb and higher number of 3-limb support phases, longer swing and stance time and prolonged stance time for hind limbs. Comparable gait adaptions have been reported in straight walk studies in fouled floor conditions on humans (Cham & Redfern, 2002a), cows

(Phillips & Morris, 2000; Telezhenko et al., 2005) and in pigs (Thorup et al., 2007; von Wachenfelt et al., 2008).

In their gait adaption to fouled floor condition, CWr pigs differed significantly from curve walking pigs on concrete (CWc) (von Wachenfelt et al., 2009b) in higher stride length and diagonality but lower duty factor. The studies of CWr and the CWc pigs were performed at the same location and with the same procedures and the pigs in the two studies were identical.

4.2.2 Gait differences between fore and hind limbs

Both CWr and CWc pigs (von Wachenfelt et al., 2009b) prolonged their hind stance phase compared with straight forward walking pigs (Applegate et al., 1988; Thorup et al., 2007; von Wachenfelt et al., 2009a), probably to increase stability as the hind limb is closer to the body's centre of gravity (Applegate et al., 1988). An increased number of 3-limb 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). However, the CWr pig stride data and the Hildebrand diagram in Figure 2 show that the pigs found a moderate gait adaption to the fouled surface to be sufficient to cope with the fouled and curved rubber flooring surface. The more moderate gait changes in the CWr pigs may have been due to the firmer foot grip from the rubber matting in fouled condition.

4.3 Kinetics

The main effort of CWc pigs in previous studies (von Wachenfelt et al., 2009b) was to reduce horizontal but also vertical forces in their gait adaption to fouled floor condition, and this was also observed in this study for the CWr pigs.

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

High mean and peak GRF_v were observed for fore limbs in both CWr and CWc pigs (von Wachenfelt et al., 2009b) compared with hind limbs in both clean and fouled floor conditions. In adapting to fouled floor condition, CWc pigs reduced their fore limb mean and peak GRF_v by 13 and 16% respectively, but the mean and peak GRF_v reduction by CWr pigs was still 5% more. In hind limbs of both CWr and CWc pigs, vertical forces were more consistent between floor conditions, although the CWr pigs increased their peak GRF_v by 8% in clean floor condition compared with CWc pigs, which shows that CWr pigs had better gait control walking the curve.

The high body weight found in CWc pig (von Wachenfelt et al., 2009b) fore limbs (approx. 60%) at mean GRF_v and the corresponding weight distribution generated by peak GRF_v (approx. 62%) was somewhat lower (approx. 56 and 59%) in CWr pigs, which corresponded to that of straight forward walking pigs (Thorup et al., 2007; von Wachenfelt et al., 2008).

The significantly higher peak GRF_v found in CWr pig hind limbs in clean floor condition, as well as lower mean GRF_v for fore limbs in fouled floor condition compared with CWc pigs (von Wachenfelt et al., 2009b), together with the overall lower weight distribution on the fore limbs in fouled condition, could imply that a gait adaption to the flooring material was more possible for CWr pigs.

Compared with CWc pigs (von Wachenfelt et al., 2009b), the CWr pigs used 6 and 19% more braking force in fore and hind limbs respectively in clean floor condition, but 44 and 28% less in fore and hind limbs, respectively, in fouled floor condition (Table 2). The use of braking forces by CWr pigs in both limbs and floor conditions was significantly different from that of CWc pigs and the shorter stance time in both floor conditions indicates that the CWr pigs had a firmer foot grip on the floor surface. The CWr pig fore limb braking force values in both clean and fouled floor conditions were consistent with values reported for straight forward walking pigs on concrete (Thorup et al., 2007) further implying that CWr pigs had a firm foot grip. But the braking forces for CWr hind limbs in clean and fouled floor conditions were 44 and 20% lower for pigs walking straight forward on concrete (Thorup *et al*., 2007). In CWr and CWc (von Wachenfelt et al., 2009b) the braking force reduction was produced by both limbs, but mainly by the fore limbs, probably as a result of higher pig weight and walking speed.

The 94% higher propulsion force in CWr pig fore limbs in fouled floor condition revealed better traction compared with CWc pigs (von Wachenfelt et al., 2009b) and the propulsion values corresponded to findings in straight forward walking pigs (von Wachenfelt et al., 2008). However the CWr pig propulsion was approx. 50% lower than the propulsion force of fore and hind limbs in fouled floor condition reported by Thorup et al., (2007). This discrepancy may be attributable to different walking speed and body weight.

The peak and minimum GRF_{lat} indicate that CWr pigs did not choose to restrict the lateral stabilising forces in order to maintain stability in either of the floor conditions. In fact CWr pigs increased the peak GRF_{lat} for the hind limbs three-fold in fouled condition compared with CWc pigs (von Wachenfelt et al., 2009b), and the CWr flooring may have allowed the pigs to lower the minimum GRF_{lat} in fouled floor condition by 44 and 50% for fore and hind limbs respectively compared with CWc flooring.

The CWr pigs responded with an approx. 50% reduction in outward and inward (except hind limbs) stabilisation force in fouled floor conditions, leaving the horizontal lateral forces minor compared with the horizontal longitudinal forces. The 6 and 19% increase in CWr pig fore and hind limb braking force respectively and the 94% increase in propulsion force compared with CWc fouled floor condition caused the CWr pigs to utilise equally high peak UCOF values in both limbs as the CWc pigs in both floor conditions.

4.3.2 Utilised cofficient of friction

The gait adaption of the CWr pigs is clearly shown in Fig. 3, where the GRFv decreases while the resulting horizontal force is mainly consistant during stance phase for both limbs in fouled floor conditions compared to clean. 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., 2009b).

(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 CWr pigs in the present study. The resulting horizontal GRF of fore limb of the curve walking cows (van der Tol et al., 2005) had a higher amplitude at 20% of stance phase and a similar high amplitude at 85% of stance phase compared to cows walking straight. A corresponding amplitude increase was not found in CWr pigs at corresponding 20 and 85% of stance phase in Fig 3.

The lower walking speed on fouled flooring can contribute to a reduction in UCOF values as reported by Cham & Redfern (2002a) and 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 an mean peak UCOF of 0.48 when negotiating a 90° turn, while the mean peak UCOF of level walking was 0.23 in clean floor conditions. However van der Tol et al. (2005) found that UCOF for cows walking a 90° curve (FP placed in the middle of the curve) in dry floor condition remained 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 current study the FP was placed just before the curve, registering the moment of curve adaption, which could explain the high CWr peak UCOF level during the stance phase but also the high peak UCOF level at toe-on and toe-off compared with straight forward walking pigs (Thorup et al., 2007; von Wachenfelt et al., 2009a). For the CWr pigs the better floor friction probably increased the floor traction and impeded the horizontal forces at impact, creating the possibility of an appropriate but smaller gait adaption (no stride length or diagonality reduction).

4.4 Floor friction and slip

The risk of slipping forward was greatest in fore limbs, confirming previous findings (Applegate et al., 1988), and the leading foot also uses the largest braking force and sets the walking direction (Redfern et al., 2001). The risk of slipping backwards is most likely for the limbs that have the highest propulsion force, i.e. the hind limbs.

4.4.1 Slips

Applegate et al. (1988) found that forward slips were very small, in general less than 1 mm, for pig fore and hind limbs. These small slips are often referred to as micro-slips (Redfern et al., 2001) and occur without the knowledge of the ‘walker’. Slip length and frequency in both CWc (von Wachenfelt et al., 2009b) and CWr pigs were higher than previously reported (Applegate et al., 1988), probably due to lower friction in fouled floor conditions combined with walking a curve.

Applegate et al. (1988) also reported that fore limbs are more affected by surface conditions than hind limbs, and argued that fore limbs at toe-on lie further from the body’s centre of gravity than hind, which would expose the fore limbs to greater horizontal forces, resulting in more slips for fore limbs.

Forward slip frequency for CWr and CWc (von Wachenfelt et al., 2009b) pig fore limbs was higher than the backward slip frequency, in agreement with Applegate et al. (1988). However, in CWr pig hind limbs there were less forward slip than backward slip. For the rubber mat flooring, forward slip frequency was reduced by 65 and 51% for fore and hind limbs, respectively, compared with concrete. The cumulative frequency of slips for CWr pigs showed less difference between left and right limbs compared with CWc pigs, which could be the result of firmer foot grip (Fig. 3).

4.4.2 Floor friction

In CWr and CWc (von Wachenfelt et al., 2009b) fouled floor condition, the PSM SCOF and SRT values for the original rubber test body were constant, but the corresponding value for the leather test body in fouled floor condition in the present study (approx. 44 BPN) was higher than for CWc flooring but considerably lower than in the Applegate et al. (1988) study. The difference in CWr and CWc pig slip frequency could perhaps have an explanation in lower DCOF value for the fouled concrete, but considering the major stride and force differences between CWr and CWc pigs the explanation is more likely to lie in deformation of the flooring material, which could provide additional friction by enabling the foot to sink into the floor and generate more traction (Nilsson, 1988; Reubold, 2008).

4.5 Gait adaption

The strategies employed by pigs to avoid slipping and falling are very much the same as those employed by humans (Cham & Redfern, 2002a), where a significant reduction in peak UCOF occurs when the subject anticipates slippery surfaces and attempted posture control. In pigs this includes more 3-feet support phases and in CWc pigs (von Wachenfelt et al., 2009b) lowered diagonality.

Thus, the biomechanics of pig walking are subject to perceptions of the environment by the individual, as also described for humans by Grönquist et al. (2003). The probability of slip and fall is determined not only by the shoe/foot, floor and exposure to contaminants, but also by the type of movement, as described for humans by Hanson et al. (1999), and in CWr pigs by positive floor deformation (Benz, 2002; van der Tol et al., 2005; Reubold, 2008).

Walking pigs in clean floor condition utilise the frictional property of floors to a greater extent than humans, but slightly less than cows (Thorup et al., 2007; von Wachenfelt et al., 2009a). The moderate curve design in this study revealed that pigs adapted to fouled floor condition but also that the flooring material can improve gait adaption and thus improve walking safety.

Sows spending 80% of their time on rubber mat flooring have been reported to improve their behavioural expression in a modified farrowing crate (Devillers & Farmer, 2008). Sows housed on rubber matting could benefit through easier standing up and lying down behaviour, as well as reduced risks of traumatic slipping and fewer claw injuries. Areas where animal movements require higher exerted animal forces, such as house areas for feeding, drinking and defecation and animal transport aisles, could benefit from rubber mat flooring.

5. Conclusions

Provoked pigs walking a curved test aisle on rubber matting use a symmetrical walking pattern with alternating 2- and 3-limb support phases. In both clean and fouled floor conditions the pigs use a clear DS walk in which the hind foot touches down slightly after the contra-lateral foot.

Pigs walking a curve in clean rubber floor condition have a cautious but confident walk and a weight distribution close to straight forward walking pigs, with 56% of body weight on the fore limbs. The pigs utilise 26% more braking force on the fore limbs than on the hind limbs, which increases to 39% in fouled floor conditions. In clean floor conditions rubber mat pigs use 6 and 19% more braking force in fore and hind limbs respectively, but in fouled floor condition 44 and 28% less in fore and hind limbs, respectively, compared with pigs walking a curve on concrete.

Pigs walking on rubber matting adapt to fouled floor condition through reduced walking speed, prolonged swing and stance time and a higher number of 3-limb support phases, but keep stride length and diagonality constant. Pig adaption in fouled floor condition comprises a threefold reduction in lateral horizontal forces, but constant braking and propulsion forces, which results in a consistent peak UCOF level in fore limbs and a 31% reduction in hind limbs in fouled floor condition.

The better traction for pigs walking on rubber matting compared with concrete are due to a more effective transmission of forces from the limb to the elastomer, dissipating the forces into energy within the material, and thus impeding the effect of centripetal force, with less displacement of body centre of gravity and thus less forward and backward slip. Forward slip frequency of pigs on rubber matting is 65 and 51% lower for fore and hind limbs respectively compared with pigs walking a curve on concrete.

The moderate curve design showed that pigs adapt to fouled floor condition but also that the flooring material can improve gait adaption and improve walking safety. To obtain more precise design criteria for pig house flooring, it is important to conduct further research where actual slips occur and relate the biomechanics to slip resistance measurements and to required movements of pigs in a pen situation.

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