

This is an author produced version of a paper published in BIOSYSTEMS ENGINEERING. This paper has been peer-reviewed and is proof-corrected, but does not include the journal pagination

Citation for the published paper:

Von Wachenfelt, H., Pinzke, S., Nilsson, C., Olsson, O., Ehlorsson, C-J.
(2008) Gait Analysis of Unprovoked Pig Gait on Clean and Fouled
Concrete Surfaces. *Biosystems Engineering*.

Volume: 101 Number: 3, pp 376-382.

<http://dx.doi.org/10.1016/j.biosystemseng.2008.09.002>

Access to the published version may require journal subscription.

Published with permission from: Elsevier Ltd.



Epsilon Open Archive <http://epsilon.slu.se>

Gait Analysis of Unprovoked Pig Gait on Clean and Fouled Concrete Surfaces

von Wachenfelt¹, H., Pinzke², S., Nilsson¹, C., Olsson³, O., Ehlorsson³, C-J.

¹ Dept. of Rural Buildings and Animal Husbandry, Swedish University of Agricultural Science, P. O. Box 86, 230 53 Alnarp, Sweden. E-mail corresponding author: Hans.von.Wachenfelt@ltj.slu.se.

² Dept. of Work Science, Business Economics and Environmental Psychology, Swedish University of Agricultural Science, P. O. Box 88, 230 53 Alnarp, Sweden.

³ Swedish Animal Health Service, P.O. Box 301 67, SE 104 25 Stockholm, Sweden.

Abstract

Inadequate floor properties are considered the primary cause of the majority of claw disorders in pigs but to date no clear relationship has been found between claw disorders and floor properties such as friction and surface abrasiveness. To determine this relationship, the factors controlling pig gait must be characterised.

This study examined unprovoked pig gait on a concrete floor in clean conditions and compared it with gait in fouled floor conditions. Kinematics were used to record gait parameters such as walking speed, stride length, swing and stance time, stride elevation together with limb support phases, gait symmetry, diagonality and duty factor.

On clean floors, pigs had an unprovoked symmetrical gait with alternating two- and three-beat support phases and a high rate of diagonality. Stride length, swing and stance time and stride elevation showed little variation. Pigs altered their gait in accordance with floor conditions to maintain gait control by reducing walking speed, lowering diagonality and employing more three-limb support phases. Pigs also shortened their stride length and prolonged their stance time.

Keywords: floor, pig, concrete, gait, kinematics.

1. Introduction

Inadequate floor properties are considered to be the primary cause of the majority of claw disorders in pigs (Gjein, 1994; Ehlorsson et al., 2002; Olsson & Svendsen, 2002; Jörgensen, 2003; Lahrman et al., 2003). A number of studies have been carried out on floors and claw disorders (Wright et al., 1972; Fritschen et al., 1976; Fritschen, 1979; Newton et al., 1980; Nakano et al., 1981; Schulenburg et al., 1986) but none of these has been able to relate claw disorder to any specific floor properties.

Floor properties such as surface friction, abrasiveness and softness have been technically described by Webb & Nilsson (1983) and Nilsson (1988), but little work has been published where the interaction between floor and animal has been studied in order to assess lameness and floor properties (Albutt et al., 1990; Thorup et al., 2007). The floors in the lying, feeding and transport areas require differing properties to comply with animal needs. Low friction can cause slips and falls, while hard floors can cause bruising and swollen legs when lying on the floor. Over-abrasive floors cause excessive wear of claws, whereas too little abrasiveness leads to overgrown claws (McKee & Dumelow, 1995). At present within the EU countries (EFSA, 2005), there is no mandatory testing and approval of floors and floor systems using animal well-being as an indicator.

To neutralise factors such as husbandry system, aggression, feeding level and high animal density, more recent investigations have focused on flooring material as the source of claw injuries (Gjein 1994; Ehlorsson et al., 2002; Olsson & Svendsen, 2002; Jørgensen, 2003; Lahrmann et al., 2003). Gait analysis could be one way of linking claw injuries to surface material conditions, using animal gait as an indicator in assessing floor properties and lameness (Applegate et al., 1988; McKee & Dumelow, 1995; Flower et al., 2005; Thorup et al., 2007).

If gait analysis can be used to characterise pig gait, it could provide an accurate and objective method of analysing alterations in claw movements that may be caused by different floor properties such as hard/soft floor surfaces, or floor conditions such as dry/fouled floor surfaces (Hottinger et al., 1996; Barrey, 1999; Flower et al., 2005; Flower et al., 2007; Thorup et al., 2007).

A body in motion can be studied by kinetic and kinematic analysis. Kinetic analysis measures locomotor forces, both external and internal to the body, while kinematic (gait) analysis studies the changes in body segment position during a specific time. In gait analysis the subject can be studied by a digital video (DV) camera and there are no repercussions on the subject as the measurements are made in the images. Various kinematic parameters can be obtained, such as stride length, stride speed, swing and stance phase (Barrey, 1999). In this way the subject can be used as an indicator of normal gait, abnormal gait, overloading or slipping motion.

A DV camera offers a non-invasive technique that also minimises pig handling, which is important since according to Main et al. (2000) because the natural response of a pig to interference or provocation is a 'short fast advancement and then a steady pace or trot'. Other methods of gait analysis are the subjective grading method (Main et al., 2000), which demands knowledge and extensive experience of the method, or the trackway analysis (Telezhenko & Bergsten, 2005). In the present study an unprovoked pig was defined as a pig not subjected to any environmental provocation that might disturb its gait.

The stride is commonly defined as a full cycle of limb motion (Clayton, 1997), 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. The stride length corresponds to the distance between two successive foot placements of the limb. Stride frequency is defined as the number of strides performed per unit time. Stride length and stride frequency are the two main components of gait speed (Barrey, 1999). In horses, stride length increases linearly with gait speed, while stride frequency increases non-linearly and more slowly (Dusek et al., 1970; Leach & Cymbaluk, 1986). The stride frequency reaches its maximum value first, to produce the acceleration, while stride length slowly reaches its maximum value (Hiraga et al., 1994).

A study on 6- to 8-month-old foals (Leach & Cymbaluk, 1986) showed that a speed increase was obtained by a longer stride length in heavier foals and a higher stride frequency in taller foals. The stride and stance duration increase with age, but swing duration remains consistent (Back et al., 1994).

According to Hildebrand (1967), 'a gait is an accustomed way of moving the legs in walking and running'. At slow speeds quadrupeds use symmetrical gaits in which the footfalls of hind and fore feet are evenly spaced in time, while in asymmetrical gaits this is not the case (Howell, 1944).

Hildebrand (1965; 1966) classified symmetrical gaits based upon speed and limb movements and defined a walk as a symmetrical gait in which 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%. The value is called the duty factor, and it expresses the relative value between stance and

stride time. Another feature that distinguishes walking gaits of primates is the prevalence of diagonality (Cartmill et al., 2002). Diagonality can be defined as the percentage of stride time in which the left footfall of the front biped follows that of a rear biped on the same side of the body (Hildebrand, 1965). Standing on more than two feet increases the size of the animal support polygon, which makes its stance more stable as it moves forward. If diagonality is between 0 and 50%, the feet touch down in order left hind, left fore, right hind, right fore. This gait is called lateral-sequence walk (LS). When the diagonality is between 50 and 100% the gait is called diagonal-sequence walk (DS), because each hind footfall is followed by the diagonally opposing fore footfall (Cartmill et al., 2002).

Gait has been studied in different species such as horse, human, dog, turkey, hen and cow (Fredricson et al., 1980; Hottinger et al., 1996; Hodson et al., 2001; Cham & Redfern, 2002; Flower et al., 2005), but few experiments have been conducted on pig gait (Calabotta et al., 1982; Applegate et al., 1988; Thorup et al., 2007).

In studying the effect of floor conditions and gait on slip and fall accidents in humans, Cham & Redfern (2002) found that a subject used both postural and temporal gait adaptations to reduce the risk of slipping when anticipating a slippery floor. A kinematic study of cows (Herlin & Drevemo, 1997) investigated the impact of slatted floor and lack of exercise during summer and found that tie-stall cows kept indoors had a shorter stance time of the fore limbs than cubicle cows kept indoors, and a shorter propulsion of the fore limbs compared to tie-stall cows kept on pasture in the summer and indoors for the rest of the year. The cows walked at a mean speed of 1.4 m s^{-1} and the mean stride duration was 1.2 seconds. Phillips & Morris (2000) found differences in cow gait on concrete floors that were dry, wet or slurry-covered, while Telezhenko & Bergsten (2005) and Flower et al. (2007) reported that rubber mats improved gait for both lame and non-lame cows compared with solid concrete floors.

Two kinematic studies have analysed pig gait as an effect of floor conditions and both found pig gait to be affected by floor conditions (Applegate et al., 1988; Thorup et al., 2007).

In most European countries, floors in pig houses are generally slatted and partly solid. De Belie (1997) found complaints from 40% of farmers concerning concrete slat durability. The slats showed degradation within five years of use, and the complaints focused specifically on increased surface roughness, enlarged gaps between slats and animal injuries. Therefore pig gait on slatted concrete floors should be investigated, but prior to such studies it is essential to obtain data on unprovoked pig gait on solid concrete floors for reference.

The objectives of this study were to use kinematics to characterise unprovoked pig gait on clean solid concrete floors and to evaluate the effect of fouled floor conditions on pig gait.

2. Materials and Methods

2.1 Animals

Ten Swedish Landrace pigs, 3 barrows and 7 gilts, were used in the study. The pigs were chosen from a farm where the pens had straw-covered solid concrete floors and were fed at moderate intensity, in order to ensure good claw health. Before and after the trial the claws were examined according to a standard protocol (Brooks et al., 1977) by a veterinary surgeon who also subjectively judged the pigs to have healthy claws and gait. The pigs were fed 3.0 kg per pig and day according to Swedish feeding norms. The average animal weight during the test period (3 d) was 113 kg (SD = 8 kg).

2.2 Experimental set-up

The test area, which comprised two rectangular pens with a connecting test aisle in between, was built in a pig house. The pens were also connected by a return aisle in the middle of the test room, which made it possible to walk the pigs back to a starting point in one of the pens. The pen areas had solid concrete flooring, while the test aisle was covered by replaceable slabs. Pig gait on the central 1.4 m of the test aisle was recorded by a perpendicularly placed DV camera (Fig. 1). During all measurements the temperature and humidity in the experimental facility were recorded every 10 min using a data logger. The indoor temperature was $13 \pm 5^\circ\text{C}$ and the relative humidity $66 \pm 15\%$.

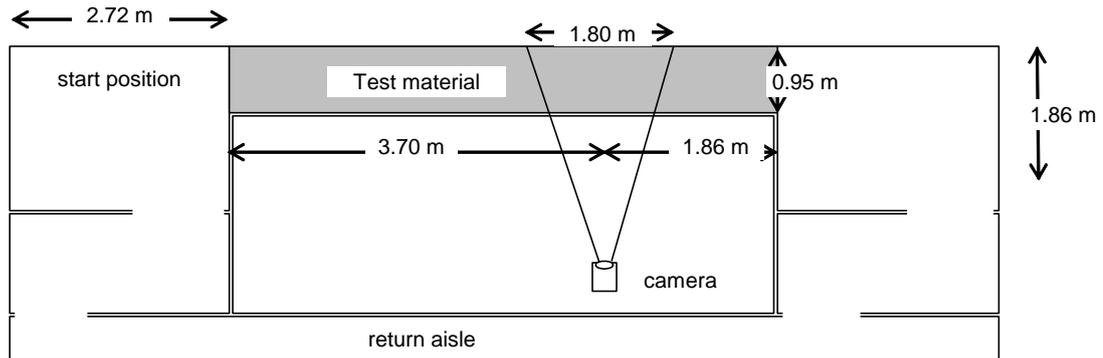


Fig. 1. Plan of the test area.

2.3 Flooring material

Solid concrete slabs representing flooring properties typical for commercial pig facilities were constructed. Each slab ($0.75 \times 0.75 \times 0.05 \text{ m}^3$) was made from a Portland cement concrete mix with a water/cement ratio of 0.45 according to SJV (1995), with welded steel mesh reinforcement in the centre. The surface finish was made with a fine broom and the slabs were allowed to cure with water application under plastic sheeting for the first 2 days and then to age for a month. A friction value of 83 British Pendulum Number (BPN) was obtained for clean surface conditions by a skid resistance tester (SRT) before the trial (ASTM, 1993). Significantly lower friction (~ 50 BPN) was recorded in the fouled concrete floor conditions compared with the clean floor.

The clean concrete floor conditions were tested first and then the fouled floor conditions. The concrete floor was fouled by pig faeces ($\sim 1.5 \text{ kg m}^{-2}$) and the total dry matter content of each batch of faeces used to foul the test aisle was recorded. Before each test of a fouled surface, the test aisle was wetted with water ($\sim 0.9 \text{ l m}^{-2}$) and was kept wet throughout the experiment by application of water and manure (0.2 l m^{-2} and 0.4 kg m^{-2} respectively) during changes of animals. The fresh manure used on the fouled surface had an average total dry matter content of 20% (SD = 2%).

2.4 Experiment

A trial consisted of 10 passes by an individual pig in each type of floor conditions. The pigs were randomly selected for each trial and two replicates were conducted for each type of floor conditions. In general, only data from the last six passages were used, which allowed pigs time to become accustomed to the surface conditions before sampling. A successful passage by an unprovoked pig was defined as a pig walking at a steady pace without stopping or

jumping, placing its fore or hind claws or both claws (separated in time) entirely on a force plate (used in another experiment). A total of 4 and 12% of the passages in clean and fouled floor conditions respectively were discarded and replaced by new passages. The average time to conduct the 10 passes was 5 min per pig.

The start of pig walking was communicated to the holding pen personnel by eye contact as the DV camera was started manually. DV data were collected at 25 Hz during passage of the moving pigs. The camera was mounted on a small tripod 1.95 m from the centre line of the test aisle with the camera lens 245 mm above the floor, which captured 1.3-1.5 m of a pig body length (average 1.4 m) in the camera viewer. The camera performed recording at VGA quality with 640 x 480 pixels.

The camera was spatially calibrated using a rectangle of known dimensions placed on the test surface before each trial. After the trial each film was imported and processed in a gait analysis programme (Vicon, Peak Motus 9.0, UK) in which the films were cut and digitalised.

Five positions of the animal were digitalised in each frame: the fore and hind claw tips 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 tips 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.

2.5 Data processing

The two dimensional (2D) coordinates were constructed by direct linear transformation. From the gait analysis programme, spreadsheets of DV data, 2D velocity and 2D coordinates were imported into an Excel spreadsheet for further processing. The average walking speed was calculated from the 2D velocity data and stride parameters from the 2D-coordinate data.

Stride length and stride time were calculated from the moment the claw tips left the floor until the claw tips left the floor again for the next step. Dividing stride length by stride time gave limb stride speed. Swing time and swing length were calculated from the moment the claw tips left until the claw tips touched the floor again. Stance time and stance length were defined as the time when the claw had physical contact with the floor (interval between claw on and claw off).

An average per pig and type of floor conditions was calculated for each stride parameter. For stance time, swing/stance time ratio and maximum stride elevation, an average was also calculated for both fore and hind limbs. The support phases were measured as percentage of time the body was supported by any number of limbs during two successive frames. When the time from the first hind footfall was greater than 55% or less than 45% of the total stride period, the cycle was considered asymmetrical. Of 260 trials of clean and fouled floor conditions, 47 were rejected. Diagonality and duty factor were calculated using the Hildebrand (1965) definition.

2.6 Statistics

Paired t-tests were used to compare differences between material conditions and to examine differences between fore and hind limbs. 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 difference between fore and hind limbs

All data were normally distributed. The pig fore limbs had lower swing/stance time ratio, but longer stance time than hind limbs in both types of floor conditions (Table 1). The stride elevation was higher in hind limbs than fore limbs, irrespective of floor conditions.

3.2 Gait differences due to surface material conditions

The pigs had a symmetrical four-beat gait, with an alternating two- or three-limb support phase. No single or four-limb support phases were observed. The number of two-limb support phases and the diagonality decreased in fouled floor conditions compared with clean, from 94% to 79% and from 73% to 61% respectively. This resulted in a change in gait pattern from a clear DS walk in clean floor conditions to a mix of DS and LS walk in fouled floor conditions (Fig. 2).

The average pig walking speed on clean concrete was significantly higher than the walking speed on fouled concrete. In clean floor conditions, the pigs had longer stride length, shorter stride time and higher stride speed than in fouled floor conditions. Furthermore, stance time was shorter for pigs in clean floor conditions compared with fouled floor conditions, whereas the swing time did not differ between floor conditions. The effects of floor condition on pig gait parameters are given in Table 1.

Table 1. Stride characteristics of 10 pigs walking in clean and fouled concrete floor conditions. A comparison between fore and hind feet and between material conditions (number of samples (n), mean and standard deviation (SD)). Data from a study in wet conditions by Applegate et al. (1988) included as reference.

Parameter	Conditions				Foot				Applegate et al., 1988		
	n	Clean Mean (SD)	n	Fouled Mean (SD)	p ¹	n	Fore Mean (SD)	n	Hind Mean (SD)	p ¹	Wet conditions Mean ²
Walking speed, m/s	117	1.65 (0.13)	116	1.31 (0.19)	***						
Stride length, m	242	0.86 (0.11)	194	0.72 (0.12)	***						140 0.63
Stride time, s	242	0.51 (0.04)	194	0.58 (0.05)	**						140 0.59
Stride speed, m/s	242	1.68 (0.18)	194	1.26 (0.27)	***						140 1.14
Swing time, s	193	0.24 (0.02)	180	0.26 (0.02)	*						140 0.24
Swing/stance time ratio	193	0.90 (0.09)	180	0.84 (0.14)	ns	193	0.81 (0.10)	180	0.93 (0.11)	***	140 0.67
Stance time, s	290	0.27 (0.02)	207	0.32 (0.04)	**	243	0.31 (0.05)	254	0.28 (0.05)	*	140 0.36
Max stride elevation, m	429	0.10 (0.01)	401	0.10 (0.02)	ns	392	0.09 (0.01)	438	0.11 (0.02)	***	

¹⁾ The probability limits for evaluating statistical significance were: * = p<0.05; ** = p<0.01; *** = p<0.001

²⁾ Mean of fine and coarse broom, fine and coarse sand and wood float concrete surfaces as a sum of front and rear claw data (data recalculated from Applegate et al., 1988)

4. Discussion

The symmetrical walking pattern with alternating two- and three-limb support phases exhibited by the pigs in the present study was similar to the walk of pigs reported by Thorup et al. (2007). It was also comparable to the walk of dogs (Hottinger et al., 1996), cows (Flower et al., 2005) and horses (Hodson et al., 2001).

In clean floor conditions the pig gait was a DS walk in which the hind foot touched down slightly later than the contralateral fore foot. The change in gait pattern in fouled floor conditions resulted in less diagonality with more overlap between fore and hind foot (DS-LS walk) which also gave rise to a larger number of three-limb support phases. The lowered diagonality on fouled surfaces was probably an effect of the lower walking speed, but was

also a way of increasing the body support area and of reducing the risk of the fore foot slipping on a unfamiliar floor surface.

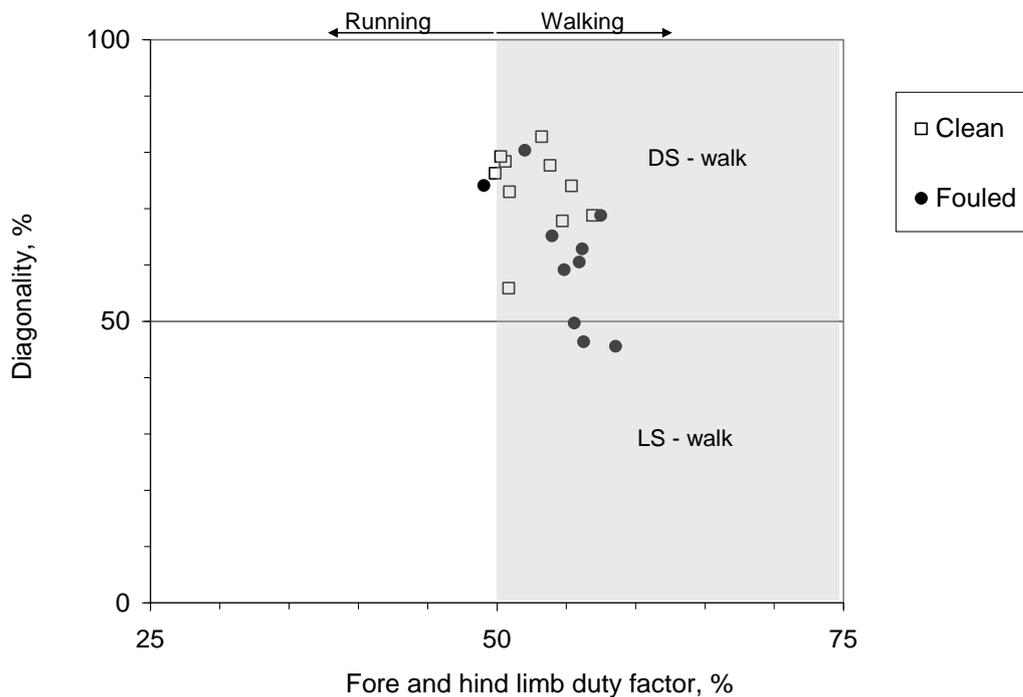


Fig. 2. Hildebrand diagram of diagonality (percentage of the cycle period by which the hind footfall precedes the fore footfall on the same side) against mean duty factor (stance period of fore and hind foot as a percentage of gait cycle) for symmetrical gaits in pigs. Open squares represent gait cycles 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).

According to Cartmill et al. (2007) a horse-type gait pattern (LS) involves about 45% of time supported on three deployed feet and most of the rest standing on two diagonally opposed feet. The difference with the findings in the present study was larger for gait in clean floor conditions but smaller for gait in fouled floor conditions.

This study confirmed that pigs adapt their gait to floor conditions. The effect of this adaption was a lower walking speed (20%), a shorter stride length (16%) and an increased stance time (16%) in fouled floor conditions compared with clean floor conditions.

These results confirm findings by Jungbluth et al. (2003) and Telezhenko & Bergsten (2005), who showed that cows reduce their walking speed and stride length on surfaces with lower friction, and by Phillips & Morris (2000), who reported that cows walk more slowly on contaminated surfaces than on dry. Thorup et al. (2007) showed that pigs (74 kg) reduce their walking speed by 16% and stride length by 7% and prolong their stance phase by 15% on a greasy concrete surface compared with a dry surface, which is also confirmed in the current study.

In this study the hind limb stance time was 10% shorter than that of the fore limbs. Applegate et al. (1988) and Thorup et al. (2007) respectively reported 14 and 8% shorter stance time in hind limbs. This difference was also reflected in the swing/stance time ratio. The difference in stance time between the present study and others (Applegate et al., 1988; Thorup et al., 2007) was probably an effect of different walking speeds, as shown in both horses and dogs (Roush & MacLaughlin, 1994; McLaughlin et al., 1996; Szalay et al., 2002). No change in stride elevation was observed between floor conditions in the present study, but

stride elevation was found to be greater in hind than fore limbs, which is in agreement with findings on gilts (Calabotta et al., 1982), but in contradiction with data on cows (Herlin & Drevemo, 1997).

Applegate et al. (1988) noted that stride length, walking speed, time and phase were influenced marginally and inconsistently by differences between wetted test surfaces, even though the range in surface friction was wide relative to commercial practice. On the other hand Thorup et al. (2007) found that stride length was shortened and stance phase prolonged only in greasy floor conditions and not in wet, which would imply that a wet floor could either maintain or decrease surface friction depending on surface roughness and evenness (Nilsson, 1988; Puumala, 2005).

The skid resistance value of fouled floor conditions in the present study (50 BPN) was considerably lower than the 70 BPN reported by Applegate et al. (1988). Compared against slip resistance values for animal housing floors in general (Richter, 2002), the SRT values obtained for the clean floor in the present study were rated 'very good to excessively rough' (70-80 BPN), which suggests that no slips occurred during clean floor conditions.

The mean body weight of the pigs remained constant during the test period, as the test was completed within three consecutive days, which means that differences in gait were not caused by differences in body size. All animals were found to be healthy in claws and gait, so the pig gait on the test aisle reflected normal pig gait on clean and fouled concrete surfaces. The walking conditions were far less demanding for the pigs in the study compared with ordinary pen conditions, in the sense that only one pig at a time walked the test aisle at a self-chosen speed under no restrictions. A pen situation often involves competition between pigs in relatively small areas where the floors can be wet and fouled, and sometimes degraded through age and food residues (De Belie, 1997), which stresses the importance of the floor properties and their interaction with animal feet (Webb & Nilsson, 1983).

The walking speed in the present study and its standard deviation were higher than those reported by Applegate et al. (1988) and Thorup et al. (2007). Those two studies had a higher DV recording frequency, which would have given greater measurement accuracy. The higher standard deviation in walking speed in the current study could have been due to the pigs being allowed to walk at their natural pace and to the number of passages per pig and floor condition being limited.

5. Conclusions

Pigs have a confident when walking unprovoked in clean floor conditions, with a gait characterised by symmetrical alternating two- and three-beat support phase with a high rate of diagonality and with low variation in stride parameters such as stride length, swing and stance time and stride elevation. To maintain their gait control, pigs alter their gait in accordance with floor conditions by reducing walking speed, lowering diagonality and employing a larger amount of three-limb support phases, as well as shortening stride length and prolonging stance time.

Floor properties should meet the demands of walking pigs in terms of friction, surface roughness, surface evenness and softness to give animals the possibility of a normal gait instead of forcing them to an altered gait to reduce the risk of slips and injury.

This study demonstrated that a non-invasive technique can be used to characterise gait, using the animal as an indicator of pig gait on different floor conditions. Future studies should investigate limb loads, foot speed and slip displacement in different floor conditions.

Acknowledgements

The authors gratefully acknowledge financial support from the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS) for the research work reported in this paper, and special funding from Crawford Foundation for digital video equipment.

6. References

- Albutt, R W, Dumelow, J, Cermak, J P, Owen, J E (1990). Slip resistance of solid concrete floors in cattle buildings. *Journal of Agricultural Engineering Research*, 45, 137-147.
- Applegate, A L, Curtis, S E, Groppe, J L, McFarlane, J M, Widowski, T M (1988). Footing and gait of pigs on different concrete surfaces. *Journal of Animal Science*, 66(2), 334-341.
- ASTM (1993). Standard test method for measuring surface frictional properties using the British pendulum tester. ASTM E303-93.
- Back, W, Barneveld, A, Schamhardt, H C, Bruin, G, Hartman, W (1994). Longitudinal development of the kinematics of 4-, 10-, 18- and 26-month-old Dutch Warmblood horses. *Equine Veterinary Journal Supplement*, 17, 3-6.
- Barrey, E (1999). Methods, Applications and Limitations of Gait Analysis in Horses. *The Veterinary Journal*, 157, 7-22.
- Brooks, P H, Smith, D A, Irwin, V C R (1977). Biotin-supplementation of diets; the incidence of foot lesions, and the reproductive performance of sows. *Veterinary Record*, 101, 46-50.
- Calabotta, D F, Kornegay, E T, Thomas, H R, Knight, J W, Notter, D R, Veit, H P, Wright, M E (1982). Restricted energy intake and elevated calcium and phosphorus intake for gilts during growth. 2. Gait characteristics analysed from 16-mm motion picture photography. *Journal of Animal Science*, 55, 1395-1404.
- Cartmill, M, Lemelin, P, Schmitt, D (2002). Support polygons and symmetrical gaits in mammals. *Zoological Journal of Linnean Society*, 136, 401-420.
- Cartmill M, Lemelin P, Schmitt D (2007). Understanding the adaptive value of diagonal-sequence gaits in primates: a comment on Shapiro and Raichlen, 2005. *American Journal of Physiological Anthropology*, 133, 822-827.
- Cham, R, Redfern, M S (2002). Changes in gait when anticipating slippery floors. *Gait and Posture*, 15, 159-171.
- Clayton, H M (1997). Gait analysis comes of age. *The Veterinary Journal*, 157(1), 5-6.
- De Belie, N (1997). A survey on concrete floors in pig houses and their degradation. *Journal of Agricultural Engineering Research*, 66, 151-156.
- Dusek, J, Ehrlein, H J, von Engelhardt, W, Hornicke, H (1970). Beziehungen zwischen trittlänge, trittfrequenz und geschwindigkeit bei Pferden. *Zeitschrift für Tierzucht und Zuchtungsbiologie*, 87, 177-188.
- EFSA (2005). The welfare of weaners and rearing pigs: effect of different space allowances and floor types. EFSA-Q-2004-077. *EFSA Journal*, 268, 1-19.
- Ehlorsson, C-J, Olsson, O, Lundeheim, N (2002). Inventory of claw health in different husbandry systems for sows. *Swedish Veterinary Journal*, 54(6), 297-304.
- Flower, F C, de Passillé, A M, Weary, D M, Sanderson, D J and Rushen, J (2007). Softer, higher-friction flooring improves gait of cows with and without ulcers. *Journal of Dairy Science*, 90, 1235-1242.
- Flower, F C, Sanderson, DJ, and Weary, D M (2005). Hoof pathologies influence kinematic measures of dairy cow gait. *Journal of Dairy Science*, 88, 3166-3173.
- Fredricson, I, Drewemo, S, Dalin, G, Hjerten, G, Bjerne, K (1980). The application of high-speed cinematography for the quantitative analysis of equine locomotion. *Equine Veterinary Journal*, 12(54).

- Fritschen, R D (1979). Housing and its effect on feet and leg problems. *The Pig Veterinary Society Proceedings*, 5, 95-98.
- Fritschen, R. D, Hogg, A, Cunningham, P J (1976). The effect of material and management on claw characteristics and lameness of growing-finishing swine. *Proc. 4th Int. Pig Veterinary Society Congress, Ames, USA.*
- Gjein, H (1994). Housing of pregnant sows - a field study on health and welfare, with special emphasis on claw lesions. *Dr Science Thesis. Oslo, Norwegian College of Veterinary Medicine, Norway.*
- Herlin, A H, Drevemo, S (1997). Investigating locomotion of dairy cows by use of high speed cinematography. *Equine Veterinary Journal*, 23, 106-109.
- Hildebrand, M (1965). Symmetrical gaits of horses. *Science (Washington)*, 150, 701-708.
- Hildebrand, M (1966). Analysis of the symmetrical gaits of tetrapods. *Folia Biotheoretica*, 6, 9-22.
- Hildebrand, M (1967). Symmetrical gaits of primates. *American Journal of Physical Anthropology*, 26, 119-130.
- Hiraga, A, Yamanobe, A, Kubo, K (1994). Relationships between stride length, stride frequency, step length and velocity at the start dash in a racehorse. *Journal of Equine Science*, 5, 127-130.
- Hodson, E, Clayton, H M, and Lanovaz, J L (2001). The hindlimb in walking horses: 1. Kinematics and ground reaction forces. *Equine Veterinary Journal*, 33, 38-43.
- Hottinger, H A, DeCamp, C E, Olivier, N B, Hauptman, J G, and Soutas-Little, R W (1996). Non-invasive kinematic analysis of the walk in healthy large-breed dogs. *American Journal of Veterinary Research*, 57, 381-388.
- Howell, A B (1944). *Speed in animals*. Chicago: University of Chicago Press. USA.
- Jungbluth, T, Bentz, B, Wandel, H (2003). Soft walking areas in loose housing systems for dairy cows. *Fifth International Dairy Housing Proceedings of the 29-31 January 2003 Conference, Fort Worth, Texas, USA, ASAE Publication Number 701P0203.*
- Jørgensen, B (2003). Influence of floor type and stocking density on leg weakness, osteochondrosis and claw disorders in slaughter pigs. *Animal Science (UK)*, 77, 439-449.
- Lahrman, K H, Steinberg, C, Dahms, S, Heller, P (2003). Prevalences of herd specific factors and limb disorders, and their associations in intensive swine production. *Berliner und Münchener Tierärztliche Wochenschrift*, 116(1-2), 67-73.
- Leach, D H, Cymbaluk, N F (1986). Relationship between stride length, stride frequency, velocity and morphometrics of foals. *American Journal of Veterinary Research*, 47, 2090-2097.
- Lemelin P, Schmitt D, Cartmill M (2003). Footfall patterns and interlimb co-ordination in opossums (Family Didelphidae); evidence for the evolution of diagonal-sequence walking gaits in primates. *Journal of Zoology (London)*, 260(4), 423-429.
- Main, D C J, Clegg, J, Spatz, A, Green, L E (2000). Repeatability of a lameness scoring system for finishing pigs. *Veterinary Record*, 147(20), 574-576.
- McKee, C I, Dumelow, J (1995). A Review of the Factors Involved in Developing Effective Non-Slip Floors for Pigs. *Journal of Agricultural Engineering Research*, 60(1), 35-42.
- McLaughlin, R M J, Gaughan, E M, Roush, J K, Skaggs, C L (1996). Effects of subject velocity on ground reaction force measurements and stance times in clinically normal horses at the walk and trot. *American Journal of Veterinary Research*, 57(1), 7-11.
- Nakano, T, Aherne, F X & Thompson, J R (1981). Leg weakness and osteochondrosis in pigs. *Pig News and Information*, 2, 29-34.
- Newton, G L, Booram, C V, Hale, O M & Mullinix, B G Jr (1980). Effects of four types of floor slats on certain feet characteristics and performance of swine. *Journal of Animal Science*, 50, 7-20.

- Nilsson, C (1988). Floors in Animal Houses - Technical Design with Respect to the Biological Needs of Animals in Reference to the Thermal, Friction and Abrasive Characteristics and the Softness of the Flooring Material. Dr Science Thesis. Rapport 61. Swedish University of Agricultural Sciences, Department of Farm Buildings, Division of Agricultural Building Technology, Lund, Sweden.
- Olsson, A C, Svendsen, J (2002). Claw health problems in gestating sows and the influence of flooring on the occurrence of injuries. Rapport 128. Swedish University of Agricultural Sciences, Department of Agricultural Biosystems and Technology, Alnarp, Sweden.
- Phillips, C J C, Morris, I D (2000). The locomotion of dairy cows on concrete floors that are dry, wet, or covered with a slurry of excreta. *Journal of Dairy Science*, 83, 1767-1772.
- Puumala, M (2005). The quality of floor surfaces in animal houses. Concrete for sustainable agriculture; agro-, aqua-, and community applications, San Lorenzo de El Escorial, Spain. Ed. Elvira Sánchez Espiosa and Miguel Angel Garcimartin Molina, Universidad Politecnica de Madrid, Spain.
- Richter, T (2002). Skid proofing of concrete stable floors. Fourth International Symposium on Concrete for a Sustainable Agriculture - Agro-, Aqua- and Community Applications (ed. De Belie, N & Sonck, B). Gent, Belgium, 61-68.
- Roush, J K, McLaughlin, R M (1994). Effects of subject stance time and velocity on ground reaction forces in clinically normal Greyhounds at walk. *American Journal of Veterinary Research*, 55, 1672-1676.
- Schulenburg, A v d, Meyer, K & Dierks-Meyer, B (1986). Orthopädische und mikrostrukturelle Untersuchungen am Klauenhorn von Mastschweinen in verschiedenen Aufstallungsarten. *Journal of Veterinary Medicine Series A-Physiology Pathology Clinical Medicine*. 33, 767-776.
- SJV (1995). Building Guidance of the Board of Agriculture - Farm Buildings Handbook. Jönköping (In Swedish), Swedish Board of Agriculture, Sweden.
- Szalay, F, Back, W, Barneveld, A, Schamhardt, H, Halos, F (2002). Comparison of video recording system with Apple Macintosh-based image analysis and modified CODA-3 systems in equine motion analysis. *Acta Veterinaria Hungaria*, 50(2), 167-176.
- Telezhenko, E, Bergsten, C (2005). Influence of floor type on the locomotion of dairy cows. *Applied Animal Behaviour Science*, 93, 183-197.
- Thorup, V, Tøgersen, F Aa, Jørgensen, B, Jensen, B R (2007). Biomechanical gait analysis of pigs walking on solid concrete floor. *Animal*, (1), 708-715.
- Webb, N G, Nilsson, C (1983). Flooring and injury: an overview. In: *Farm Animal Housing and Welfare* (ed. Baxter, S H, Baxter, M R, MacCormack, J A D). Martinus Nijhoff, Boston, USA. 226-259.
- Wright, A L, Osborne, A D, Penny, R H C & Gray, E M (1972). Foot-rot in pigs: experimental production of the disease. *Veterinary Record*, 90, 93-99.