Effect of Floor Condition on Pig Gait

A Kinematic and Kinetic Study

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Doctoral Thesis
Swedish University of Agricultural Sciences
Alnarp 2009

Acta Universitatis agriculturae Sueciae

2009: 81

Dedication:

To Särimner, the everlasting pig of Valhalla…

Cover: Pig walking a line on test aisle
(All photos in the thesis were taken by the author, unless otherwise mentioned)

ISSN 1652-6880
ISBN 978-91-576-7428-9

Print: Repro, Alnarp 2009

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Abstract

Unhealthy legs and claws in pig production are a persistent problem, a primary reason for which seems to be inappropriate floor properties in the pig pen. Inadequate frictional properties or low coefficient of friction (COF) may result in slippery floors and slip injuries to pigs.

This thesis presents basis of design criteria for pig house floors with the aim of minimising the number of claw disorders. Parameter values were determined by pig gait studies in a gait analysis laboratory, where the pigs walked a straight or a curved test aisle. The gait was recorded by a force plate and a perpendicularly placed digital video camera as the pigs walked the test aisle. The specific aims of the four studies included in the thesis were to: 1) characterise pig gait and describe the effect of clean and fouled floor conditions for pigs walking a line on solid concrete, walking a curve on solid concrete and walking a curve on rubber mat; 2) determine the utilised COF (UCOF) of the walking pigs and compare it with measured dynamic COF (DCOF); and 3) analyse pig slip in different floor conditions. A set of parameter values characterising pig gait in clean and fouled concrete floor conditions were obtained by kinematic and kinetic methods. The data showed that pigs walking a straight line adapted their gait to fouled floor conditions. Pigs were able to adapt to walking a curve in clean floor conditions but the observed adaptation was not enough for safe walking in fouled floor conditions, where UCOF exceeded DCOF. Walking a curve on fouled rubber mat gave better traction and reduced forward and backward slips by over 50% compared with walking a curve on fouled concrete. The discrepancy between UCOF and measured DCOF observed in the studies could be due to the friction measuring device underestimating the actual risk of slipping and falling in fouled floor conditions, especially when walking a curve. Additional studies are needed to provide pig producers with more detailed information, *e.g.* guidelines for required COF values in pig pen situations where the required motion and speed of motion are determined. An appropriate data set for COF measurements at farm level can bring safer and more slip-resistant floor solutions in the future.

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

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Golvunderlagets inverkan på grisars gång – en kinematisk och kinetisk studie

Klöv- och benskador är ett återkommande problem i svinproduktionen, där huvudorsaken tycks vara olämpliga golvegenskaper i grisboxen. Otillräckliga friktionsegenskaper eller låg friktionskoefficient (COF) kan resultera i hala golvytor och halkskador hos grisarna.

Denna avhandling presenterar några förutsättningar för utformning av golv i grisstallar med målsättning att minimera antalet klövskador. Parametervärden har fastställts genom gånganalys i laboratorium, där grisarna fick gå på en rak gångbana eller gångbana med kurva. Grisarnas gång på gångbanan registrerades med hjälp av en tryckplatta och en vinkelrätt placerad digital videokamera.

De specifika syftena med de fyra studierna som ingår i avhandlingen var att: 1) karaktärisera grisars gång och beskriva inverkan av ren och gödselbelagd betong-golvyta då grisarna gick på rak gångbana eller på gångbana med kurva, samt ren och gödselbelagd gångbana med kurva belagd med gummimatta; 2) bestämma den utnyttjade COF (UCOF) hos de gående grisarna och jämföra den med uppmätt dynamisk COF (DCOF); och 3) analysera grisarnas halkning under olika golvförhållanden.

Ett antal parametervärden som karaktäriserar grisars gång på rent och gödsel-belagt betonggolv erhölls genom den kinematiska och den kinetiska metoden. Resultaten visar att grisar som går på en rak gångbana anpassar sin gång till gödslade golvförhållanden. Grisarna klarade av att anpassa sin gång till gångbana med kurva på rent underlag men den observerade anpassningen var inte tillräcklig för säker gång under gödselbelagda golvförhållanden, då UCOF översteg DCOF. Gödsel-belagd gummimatta gav bättre grepp och reducerade framåt- och bakåt halkningar med 50% jämfört med gödselbelagt betonggolv då grisarna gick på gångbana med kurva.

Skillnaden mellan UCOF och uppmätt DCOF som observerades i studierna kan ha orsakats av att friktionsmätaren underskattat den verkliga risken för halkning under gödslade golvförhållanden, speciellt vid gångbana med kurva. Fortsatta studier behövs för att förse grisproducenter med mer detaljerad information, t ex. rekommendationer med nödvändiga COF värden för golv till grisboxar, där grisarnas nödvändiga rörelse och rörelsehastighet är bestämd. Ett lämpligt dataunderlag för uppmätning av COF på gårdsnivå kan ge säkrare golv med bättre halkmotstånd i framtiden.

Nyckelord: gris, gång, golv, betong, gummimatta, friktion, kinematik, kinetik, halkning.

Contents

List of Publications

This thesis is based on the work contained in the following papers, which are referred to in the text by their Roman numerals:

I 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 101, 376-382.*

II von Wachenfelt, H., Pinzke, S., Nilsson, C., Olsson, O. & Ehlorsson, C-J. (2009). Force analysis of unprovoked pig gait on clean and fouled concrete surfaces. *Biosystems Engineering 104, 250-257.*

III von Wachenfelt, H., Pinzke, S. & Nilsson, C. (2009). Gait and force analysis of provoked pig gait on clean and fouled concrete surfaces. *Biosystems Engineering*. doi:10.1016/j.biosystemseng.2009.08.008

IV von Wachenfelt, H., Nilsson, C. & Pinzke, S. (2009). Gait and force analysis of provoked pig gait on clean and fouled rubber surfaces. *Biosystems Engineering*. Manuscript.

Paper I-III are reproduced with the permission of the publisher.

My contribution to the papers included in this thesis was as follows:

I Planned the experiment, carried out the experiment, processed the data and wrote the paper in collaboration with co-authors.

II Planned the experiment, carried out the experiment, processed the data and wrote the paper in collaboration with co-authors.

III Planned the experiment, carried out the experiment, processed the data and wrote the paper in collaboration with co-authors.

IV Planned the experiment, carried out the experiment, processed the data and wrote the paper in collaboration with co-authors.

Abbreviations and terms

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.
CWc	Pigs walking a curved test aisle on concrete floor.
CWr	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 objects 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 depending on the character of the mechanical and molecular interactions between the two surfaces in contact.
FP	Force plate.

GRF	Ground reaction force, measured with an FP. GRF_v Vertical GRF GRF_{long} Longitudinal GRF (in 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.
Objective method	Kinetic and kinematic analyses based on recorded data.
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 the foot is in contact with the ground.
Stride elevation	Maximum vertical displacement between two consecutive foot strikes of the same foot.
Stride length	Horizontal displacement between two consecutive foot strikes of the same foot.
Stride speed	Stride length/stride time.
Stride time	Time interval between two consecutive foot strikes of the same foot.
Subjective method	Analyses based upon an observer's scoring system.
SWc	Pigs walking a line in a straight test aisle on concrete floor.
Swing time	Time 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).

Background

Lameness, leg weakness and claw injuries are commonly referred to as leg problems. These disorders have been documented in international research for many years but the principal cause of the problem has been hard to find.

Investigations in the past decade have focused on flooring as the source of lameness due to claw injuries. Slatted floors and solid floors without straw cause claw problems to a larger degree than littered floors and, overall, inadequate floor properties seem to be the primary cause of the majority of claw disorders. There is thus a need for studies examining the effect of floor material on pig gait in order to establish floor properties that correspond to the biological needs of the pigs and thus minimise the number of claw disorders directly linked to floor system.

This thesis presents four studies of pig gait that analyse how pigs walk in different floor conditions and floor materials. These data were then analysed to determine floor properties that better correspond to the biological needs of the pigs.

Introduction

More efficient diets and animal breeding have produced faster growing pigs and these are housed in an environment that has been modified to maximise profits and minimise losses. However, leg weakness and leg injuries are closely connected to modern husbandry systems for almost all domestic animals, for a multitude of reasons. For many decades leg problems have been documented in research in different countries, with different housing systems, feeding regimes and flooring systems, to find the principal cause of the problem. This research has accumulated knowledge about some of the factors that determine claw health, *e.g.*:

- Genetic predisposition to leg/foot problems (Wilson *et al.*, 1980; Webb and Nilsson, 1983; Lundeheim, 1987; Dewey, 1999; Jørgensen and Andersen, 2000)
- High feeding level (Gröndalen, 1974; Reiland, 1978; Wilson *et al.*, 1980; Jørgensen, 1995)
- Limited possibilities for exercise, small stall space or high animal density (Elliot and Doige, 1973; Fredeen and Sather, 1978; Hacker *et al.*, 1994; Petersen and Oksbjerg, 1998; Jørgensen, 2003)
- Inappropriate flooring (Wright *et al.*, 1972; Fritschen, 1979; Newton *et al.*, 1980; Nakano *et al.*, 1981; von der Schulenburg *et al.*, 1986).

Unplanned removal of sows, especially young sows with few pregnancies, is high due to reproductive failure, lameness and mortality (Boyle *et al.*, 1998; Kirk *et al.*, 2005; Sanz *et al.*, 2007; Engblom *et al.*, 2008). Approximately 10% of unplanned removals are slaughtered due to lameness arising from arthritis (inflammatory) followed by osteochondrosis and fractures (Kirk *et al.*, 2005; Engblom *et al.*, 2008). Kirk *et al.* (2005) found that the reason for culling was related to the locomotive system in 75% of culled sows, and that arthrosis (caused by wear) was present in 88% of culled sows and 93% of spontaneously dead sows.

In the past decade the economic and ethical importance of sow culling has received increasing attention. A decreased removal rate of sows reduces the costs for replacement gilts and increases net income. At least three litters are required from a sow before she gives a net income for the producer, according to Lucia *et al.* (2000) and Stalder *et al.* (2003).

Other investigations have concentrated on flooring as the source of claw injuries. Gjein (1994), Mouttotou *et al.* (1999), Jørgensen (2003), Lahrmann *et al.* (2003) and Heinonen *et al.* (2006) found that slatted floors and solid floors without straw cause claw problems to a larger degree than littered floors. Mouttotou *et al.* (1999) observed claw injuries in 94% of 4038 finishing pigs from 21 farms and found a connection between claw injuries and different types of floors.

Table 1. *Influence of different floor conditions on claw health (Gjein, 1994)*

Floor conditions	Effect on claw
Soft floor	Overgrowth of claw horn.
Slippery floor	Injuries, especially in accessory digits.
Worn, abrasive	High wearing rate, many heel injuries.
Manure/urine-fouled	Softened claw horn, infections.
Slatted floor	Wounds and formation of cracks.
Different floor levels	Wounds and formation of cracks.
Little or no straw	Injuries, especially in the rear part of the claw.

The primary reason for most leg and claw injuries seems to be inappropriate floor properties (Gjein, 1994; Jørgensen, 2003; Lahrmann *et al.*, 2003). Claw infections are associated with worn, degraded and dirty floors with accumulation of pathogens, which can promote infections (Gjein, 1994). Claw infections and lameness increase in sow housing systems because of small pen size (<2 m^2) and/or if there is a slatted floor in the pen (Gjein, 1994).

Physical injury is produced by mechanical stress (Webb and Nilsson, 1983). This is a precisely defined physical quantity and requires forces being exerted in conflicting directions in a tissue. The cause of the mechanical stress can be internal or external to the animal and can be physical or chemical in origin, but the end result is the same – the physical destruction of a structure.

Webb and Nilsson (1983) list five important floor properties that affect animal claws in livestock buildings: friction, abrasiveness, hardness, surface profile and thermal properties.

Table 2. *Floor properties and how they affect animals in livestock buildings (Webb and Nilsson, 1983)*

Floor property	Effect on claw
Friction	Determines floor condition, foot/floor interaction, slips, recovery/injury, traction.
Abrasiveness	Determines the rate of claw wear, too little or too much can lead to injury.
Hardness	Determines the maximum stress that a tissue receives. Deformation reduces contact pressure and mechanical stress.
Surface profile	Sharp edges cause high stresses in underlying tissue leading to injury, small surface-to-void irregularities can lead to the same effect.
Thermal properties	Floor temperature can affect posture, behaviour and physiology.

Slippery floors may cause damage to pig claws and joints through traumatic injuries, fall-related injuries and impact injuries. If the floor is too rough, pressure induces injuries of the sole (McKee and Dumelow, 1995).

According to Webb and Nilsson (1983), it is not sufficient to simply measure floor properties, since it is the relationship between injury and one of the indices of stress and floors that is important. The ideal study should measure both the floor and its biological consequences (Webb and Clark, 1981a).

Claw and flooring properties, friction

Pig claw properties

Through investigating peak hoof pressures and the compressive strength of the hoof wall, Webb (1984) concluded that pigs mainly walk on their outer digits, although the inner toe is used. The peak pressure on the foot is almost independent of weight, and the total contact area varies almost linearly with weight, which means that the pig claw is flexible (Webb, 1984) and in frictional terms is best considered an elastomer (McKee and Dumelow, 1995). Webb (1984) points out that this may explain why outer digits receive more injuries, but total load-bearing alone does not explain the differences in the incidence of injury between fore and hind limbs.

Figure 1. Underside of a healthy pig claw (photo by A-C Olsson).

Figure 2. Injuries to the horn of the pig claw (photo: A-C Olsson).

Figure 3. Injuries to the digits of the pig claw (photo: A-C Olsson).

A recent investigation of wild boars showed no signs of osteochondrosis in the examined growing wild boars (Ehlorsson *et al.*, 2006). Measurements of the claw size of adult wild boars showed that the front claw was on average approx. 6% larger than the hind claw and that there was no asymmetry of the digits on the front and hind limbs. This is in contrast to domestic pigs, which often have smaller inner than outer digits. Toe angle measurements showed the same figures for wild boar front and hind legs, with an average of 38°, compared with 50-60° in domestic pigs. These observed differences between the domesticated and wild boar as regards toe angle, claw size and digit symmetry, together with genetic and environmental factors, may explain the apparent differences in leg and claw health in favour of the wild boar (Ehlorsson *et al.*, 2006).

Animal responses to flooring properties

It has been shown that there are benefits from outdoor exercise not only for cows in tie-stalls (Gustafson, 1993) but also for animals in loose-housing systems (Regula *et al.*, 2004). For cattle, there is a need to walk at least 3-4 km per day to stay in good physical condition (Phillips, 2002). Forced exercise of boars has been shown to improve leg conformation and gait compared with unexercised boars, as well as decreasing the degree of leg weakness and delaying its onset (Perrin and Bowland, 1977). It is reasonable to assume that exercise would have the same effects on growing pigs and would probably improve their resistance to injury.

In pig houses, slatted and solid floors are mainly made from concrete. In a survey 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.

Few studies examining floor properties together with the biological response have been carried out in pigs (Applegate *et al.*, 1988; Thorup *et al.*, 2007). Studies of piglet and weaner preferences as regards slatted floors by Farmer (1982) showed that floors with higher coefficient of friction were selected for walking and lying. However, floors were not selected as regards how injurious they were.

Holmgren *et al.* (2008) studied foot and skin lesions in different types of farrowing pens, unfortunately with unsatisfactorily defined floor properties, which resulted in inconclusive results regarding concrete flooring in farrowing pens.

For technical and financial reasons, flooring and flooring systems in animal houses are often made from hard materials, which mean that they do not deform under the pressure of an animal foot. This is in contrast to the surface of a pasture, which is deformable by foot pressure (Hernandez-Mendo *et al.*, 2007). Attempts have been made to improve the properties of concrete through covering it in deformable material.

Elastomers such as vulcanised rubber have special stress and strain behaviour in the sense that the stress is not proportional to the strain but if unloaded it recovers to its original status. In decreasing stress the rubber dissipates energy within the elastic material, which makes rubber a very good shock absorber, where the mechanical energy is converted to internal energy, *e.g.* a rise in temperature (Sears and Zemansky, 1973).

The work of Benz (2002) showed the beneficial effects of rubber flooring for cow locomotion, claw health and animal welfare. Recent studies of rubber walkways in loose housing systems have confirmed these effects in cow locomotion (Rushen *et al.*, 2004; Telezhenko and Bergsten, 2005; Rushen and Passille, 2006; Boyle *et al.*, 2007; Flower *et al.*, 2007; Rushen *et al.*, 2007; Telezhenko *et al.*, 2007; Platz *et al.*, 2008; Reubold, 2008). However, only three of those studies recorded floor properties together with the biological response in cows (Benz, 2002; Telezhenko and Bergsten, 2005; Reubold, 2008).

Rushen *et al.* (2006) examined the effects of roughness and degree of compressibility of flooring on the locomotion of dairy cows and found that standard engineering measures of the floor properties may not predict effects of the floor on cow behaviour well. However, their conclusions may have been confounded because no floor properties were measured on-site during the experiment. 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 in dairy cows.

Sows choose to spend more than 85% of their time on rubber mat flooring in a modified farrowing crate compared to sows in traditional crates with plastic-coated expanded metal flooring (Devillers and Farmer, 2008). The rubber mat sows have been reported to improve their behavioural expression. 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.

Boyle *et al.* (2000) reported that providing sows with rubber mats in the farrowing house could greatly improve sow welfare on metal slatted floors, through comfort and reduced slipping, but pointed out that further research is needed to identify materials that are less abrasive to the skin of piglet front legs. The quality of the floor is essential to the welfare of piglets as abrasions often are recorded in newborn piglets, and such lesions may lead to lameness. Zoric *et al.* (2009) found that piglets in pens with concrete floors with mended cracks and surface irregularities complemented with some straw had a lower prevalence of abrasions and lameness. The most severe abrasions to carpus and sole were found in a system with a new solid concrete floor with a concrete slatted floor over the dunging area, while the least damage was observed in a deep litter system with peat.

Friction

Friction is one of the five floor properties which affect animal injuries in livestock buildings (Webb and Nilsson, 1983). The purpose of friction measurements is the prevention of slipping and tripping injuries by comparing measured values of floor friction properties with threshold friction values for safe walking.

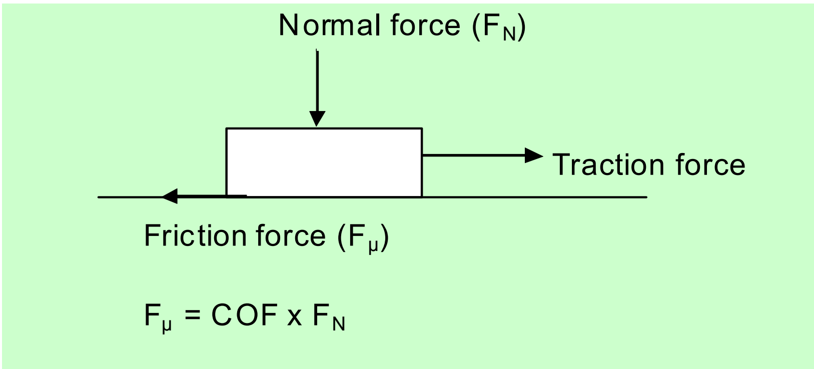

Figure 4. Relationships between normal, traction and friction forces and coefficient of friction (COF).

Floor properties are often summarised by the coefficient of friction (ratio between frictional and normal force, F_{μ}/F_N), which is the most informative technical parameter of slip resistance (Chang *et al.*, 2001a).

The coefficient of friction (COF) determines the horizontal (frictional) force that can be generated between the contact surfaces of two objects in relation to the vertical force between these objects (Hall, 1995; Chang *et al.*, 2001a). The amplitude of the frictional force depends on the character of the mechanical and molecular interactions between the two surfaces in contact (Figure 4). On horizontal surfaces the COF is determined by the ratio of the horizontal and vertical forces, which is referred to as static COF (SCOF) just before and when objects start to slide relative to one other, and dynamic

COF (DCOF) during sliding. During sliding, the magnitude of DCOF remains constant and is theoretically lower than the SCOF (Hall, 1995).

Measurements of COF and UCOF

Webb and Nilsson (1983) found a problem in comparing friction measurements reported in the literature because of the absence of a standardised protocol describing the physical characteristics of the floors tested. Another problem was that there was no standard floor that all studies used as a reference.

In a review of slip-resistance meters for human floors, Strandberg (1983) found that many of the meters were designed to gauge the static friction, although research concluded that any frictional force requires motion. Thus the actual forces and motions of slip must be known if real slip-resistance is to be measured. Biomechanical data (Strandberg, 1983) from an experiment with human subjects indicated that slip-resistance corresponds much better to DCOF than to SCOF. Since subjects never fell if the sliding velocity peak remained below 0.5 m/s, slip resistance testing seems to be more relevant if the relative motion is kept within the range 0-0.5 m/s.

The pendulum striker devices (*e.g.* SRT) produce an impact at the moment of contact, typical for a heel strike in normal walking, followed immediately by the COF measurement (Chang *et al.*, 2001b). This results in a near constant force between the slider and the surface. The SRT device can be used for floor testing on dry, wet and contaminated surfaces but measurements can be affected if the slider hits a bump in a relief surface at the moment of impact (Chang *et al.*, 2001b).

Static or dynamic COF testing without impact, *i.e.* test methods applying constant load, tend to lead to poorer separation of the interacting surfaces due to lower hydrodynamic pressure generation in the contaminant film (Moore, 1972). Therefore, they tend to produce higher COF values than the methods applying impact loading when test conditions are identical. Non-impact measurement techniques may underestimate the actual risk of slipping and falling, particularly when wet, oily or greasy conditions are encountered (Chang *et al.*, 2001a).

In most cases, slip and fall accidents arise from an inability to adapt to floor conditions. The foot forces that are generated when a foot comes into contact with the ground require friction to prevent slip (Hanson *et al.*, 1999). An increasingly slippery floor will result in a high risk of slipping if the subject does not alter its gait (Redfern and DiPasquale, 1997). The friction that a human subject requires from the floor surface during walking, or the utilised coefficient of friction (UCOF), can be determined from force plate (FP) recordings of ground reaction forces (GRF). The UCOF is defined as the ratio between the horizontal and normal components of the GRF generated by a subject during floor foot contact (Redfern *et al.*, 2001).

Slip occurs when UCOF exceeds COF. The probability of slip occurs either when the subject's UCOF increases or when the available friction from the floor surface decreases (Hanson *et al.*, 1999). While UCOF is determined by the ratio of shear to normal GRFs, there is a probability that postural changes and changes in gait pattern can influence the risk of slipping (Cham and Redfern, 2002a). In addition, the peak UCOF has been shown to increase with increasing walking speed (Powers *et al.*, 2002). Cham and Redfern (2002a) found that a human subject used both postural and temporal gait adaptations to reduce the risk of slipping when anticipating slippery floor conditions. Hanson *et al.* (1999) reasoned that to make the environment slip-safe, it needed to be designed such that the probability of slip and fall would be extremely low, for which the measured DCOF was greater than the peak UCOF. However, they also concluded that this is not only determined by the shoe/foot, floor and degree of fouling, but also the types of movements required by the subject, *i.e.* fast or slow (Hanson *et al.*, 1999) in accordance with Powers *et al.* (2002).

In cows, slip direction and magnitude have been investigated by Albutt *et al.* (1990). Jungbluth *et al.* (2003) and Telezhenko and Bergsten (2005) showed that cows reduce their walking speed and stride length on surfaces with lower friction, while Phillips and Morris (2000) reported that cows walk more slowly on contaminated surfaces than on dry. How the UCOF values of cows differ during different locomotion situations was shown by van der Tol *et al.* (2005). Typical floor COF values for cows range from 0.25 to 0.55 depending on floor conditions and testing method (Webb and Nilsson, 1983; Phillips and Morris, 2001). A sufficient COF value for animals standing or in locomotion is suggested to be at least 0.35-0.40 (Webb and Nilsson, 1983).

For pigs in intensive production, often housed on concrete floors, the pig pen often involves competition in relatively small areas, where the floors could be wet and fouled, sometimes degraded (De Belie, 1997). In pig gait, the COF depends on claw properties, flooring and the surface (floor conditions such as dry, wet or manure-fouled). The UCOF values for required pig movements in pig pens are to our knowledge still unknown.

A material that increases floor friction forces at toe-on and toe-off in absorption of foot pressure and horizontal forces at impact, could thus reduce the risk of slipping, promoting safe walking (Nilsson, 1988; van der Tol *et al.*, 2005). Recent studies in cows and pigs have assessed relationships between floor properties, gait and, in some cases, lameness by kinematics/kinetics (Hottinger *et al.*, 1996; Barrey, 1999; Hodson *et al.*, 2001; Flower *et al.*, 2005; Flower *et al.*, 2007; Thorup *et al.*, 2007).

Gait measurement methods

Subjective methods

Subjective gait measurements have been used in assessments of lameness in cattle (Manson and Leaver, 1988; Whay *et al.*, 1997) and pigs (Main *et al.*, 2000). The gait assessments are based on an observer's scoring system reflecting changes in gait leading to lameness. Lameness scoring can be a helpful tool in evaluation of the lameness disorder, but it does not provide sufficiently accurate measurements of gait (Flower *et al.*, 2006). Although the gait scores can be compared, the accuracy of the scoring can be influenced by the observer's skill and perception (Whay *et al.*, 1997; Main *et al.*, 2000; Engel *et al.*, 2003). Flower *et al.* (2005) reported that scoring systems had failed to relate to specific ailments up to then, and could fail in consistency between observers or even with the same observer if the scoring system was not validated.

Flower *et al.* (2005) quantified and validated the gait of cows with and without claw pathologies by using kinematic gait analysis. Moreover they tested and validated an explicitly defined overall gait score and individual behavioural gait attributes.

Objective methods

Objective methods such as kinetics and kinematics could avoid some drawbacks that the subjective grading methods have. Kinetics is the study of forces involved in motion (Hall, 1995). Kinetic studies in animals use force plate (FP), force shoes or pressure sensors to obtain ground reaction forces (GRF) which are the counter forces of those that are exerted by the animal limb. The GRF data provide information on vertical and horizontal forces exerted by the animal in different floor conditions, which can be used in assessing the forces used by the animal (Hottinger *et al.*, 1996; Hodson *et al.*, 2001; van der Tol *et al.*, 2005; Thorup *et al.*, 2007) (see section on Measurements of COF and UCOF).

Kinematics is the study of changes in position of body segments over time, without reference to the forces involved in motion (Hall, 1995). Small spheres as markers are commonly attached to the skin at standard anatomical locations, and high-speed cinematography or a digital video (DV) camera captures the movement of the animal. Video records are transferred to motion analysis software capable of digitising a sequence of movements automatically, and the data collected can provide information on the linear and angular displacements, velocity and accelerations of each marker (Barrey, 1999; Clayton and Schamhardt, 2001).

Kinematic gait analysis can be performed without repercussions on the subject as the measurements are made in the DV images, and the subject can be used as an indicator of normal gait, abnormal gait, overloading or slipping motion. The non-invasive technique that the DV camera offers also minimises animal (pig) handling, which is important since according to Main *et al.* (2000), 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 include the grading method (Main *et al.*, 2000), which demands knowledge and extensive experience of the method, and trackway analysis, which is based on footprint measurements (Telezhenko and Bergsten, 2005).

Kinetic and kinematic analyses have been successfully used in studying gait and performance in horses (Drevemo *et al.*, 1980; Merkens *et al.*, 1988; Gustås *et al.*, 2007) and dogs (Jayes and Alexander, 1978; Hottinger *et al.*, 1996). Until recently, few kinematic or/and kinetic studies had been carried out in cattle (Herlin and Drevemo, 1997; Flower *et al.*, 2005; van der Tol *et al.*, 2005; Flower *et al.*, 2006; Flower *et al.*, 2007) and even fewer in pigs (Calabotta *et al.*, 1982; Thorup *et al.*, 2007).

Gait parameters

Kinematic gait analysis allows basic gait parameters such as walking speed, stride length, stride speed, swing and stance phase to be determined (Barrey, 1999; Clayton and Schamhardt, 2001). Gait analysis was first based on a quantitative analysis in the 1960s, when the distinctive properties of any symmetrical gait could be expressed as a point on a bivariate plot (Hildebrand, 1965; 1966). 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, *i.e.* in which the time interval from each biped's left footfall to its next right footfall equals one-half of its stride period. Such gaits are called symmetrical because the second half of the quadruped gait cycle repeats the first half with left and right sides reversed. 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 gaits of walking 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 the 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).

Kinetic and kinematic pig studies

Webb and Clark (1981a; 1981b) described measurements of walking pig claws in terms of GRF, but did not quantify any parameters. In studying the effect of dietary treatments on gait characteristics, Calabotta *et al.* (1982) used motion picture photography of pigs walking a treadmill to quantify measurements such as torso length, distance between hooks and pastern angle relative to horizontal, but no measurement related to gait performance.

Applegate *et al.* (1988) performed a kinematic study of 8 pigs (30-40 kg) in which the objective was to relate the number of slips of the pigs passing along a test aisle to floor properties and floor condition. A number of different concrete floors were tested, all wetted for one hour prior to testing. The floor friction was tested by an SRT friction device before and after pig passage along the test aisle.

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. However, hind limb stance time was 9% shorter than fore limb. The floor friction influenced the number of forward and backward slips significantly, and the fore limbs slipped more than the hind limbs. However, the forward slips observed were very small, in general less than 1 mm for pig fore and hind limbs.

The most comprehensive study yet of biomechanical gait analysis of pigs was performed by Thorup *et al.* (2007). The study involved both kinetic and kinematic analysis of pigs walking a straight test aisle with three concrete floor condition categories (dry, wet and greasy (rapeseed oil)). In all, 10 different pigs with a body weight of approximately 75 kg were used for each floor condition category. The pigs were found to adapt to the greasy floor conditions by lowering their walking speed (16%) and peak UCOF. Furthermore the pigs reduced their stride length (7%) and increased their stance time (15%) in greasy conditions compared with dry floor conditions. The fore limbs differed from hind limbs biomechanically in receiving higher peak vertical forces, as well as higher mean vertical forces and longer stance time than the hind limbs.

Aims of the thesis

The overall aim of this thesis was to:
Determine design criteria for pig house floors in order to minimise the number of claw disorders.

Specific objectives of the thesis were to:
- Characterise pig gait on clean solid concrete floors (Papers I, II)
- Evaluate the effect of fouled floor conditions on pig gait (Papers I, II)
- Determine UCOF, using the animals as indicators, compared with measured DCOF (Papers II, III, IV)
- Characterise provoked pig gait (walking a curve) on a clean solid concrete surface and evaluate the effect of surface fouling on pig gait by use of kinematics and kinetics (Paper III)
- Characterise provoked pig gait (walking a curve) on a clean rubber surface and evaluate the effect of surface fouling on pig gait by use of kinematics and kinetics (Paper IV)
- Analyse pig slip in different floor conditions (Papers II, III, IV)

Hypotheses examined in the thesis

The hypotheses examined in this thesis were as follows:
- Pig gait in different floor conditions can be characterised by a combination of kinematic and kinetic methods (Papers I, II)
- Pigs adapt their gait to fouled floor conditions when walking a straight line (Papers I, II)
- Pigs adapt their gait when walking a curve (Paper III)
- Pigs adapt their gait to a soft floor when walking a curve (Paper IV)
- A soft floor improves walking safety for pigs walking a curve (Paper IV)

Structure of the thesis

The experimental conditions used and the parameters examined in Papers I-IV of this thesis are summarised in Table 3 and the structure of the thesis in Figure 5.

Table 3. *Conditions used in the four pig gait studies (Papers I-IV)*

Paper	Test aisle	Floor material and condition	Measuring method
I	Straight	Concrete, clean and fouled	Kinematic
II	Straight	Concrete, clean and fouled	Kinetic, friction and slip
III	Curve, 30°	Concrete, clean and fouled	Kinematic, kinetic, friction and slip
IV	Curve, 30°	Rubber mat, clean and fouled	Kinematic, kinetic, friction and slip

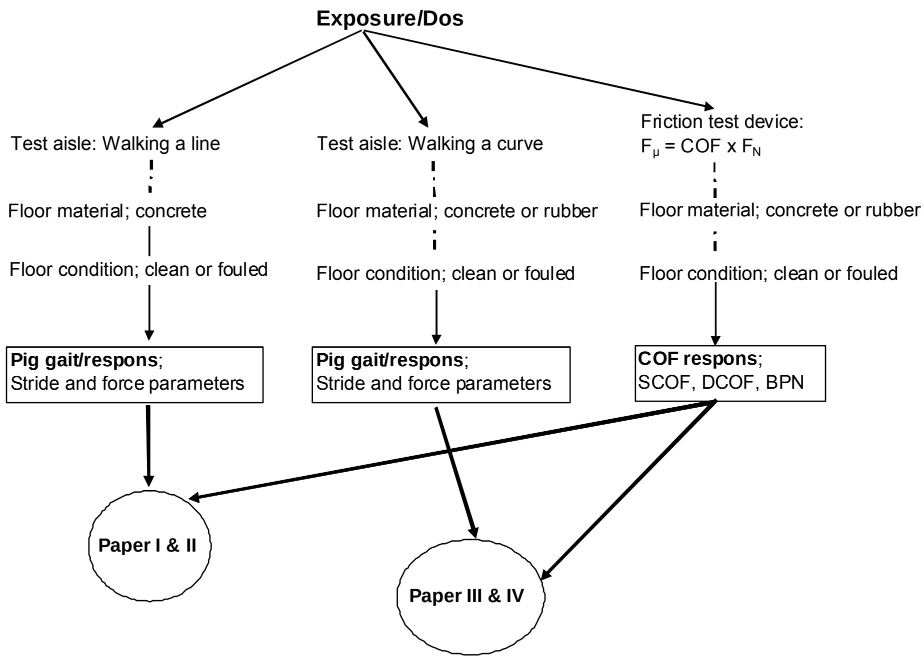

Figure 5. Structure of the thesis

Materials and methods

Animals

Two experiments of gait analyses were performed and reported in Papers I–IV, where two batches of ten Swedish Landrace pigs (3 barrows and 7 gilts in each batch) were used (one batch in each experiment). The pigs, which came from a known 'flooring background', were examined as regards feet and gait by a veterinary surgeon according a standard protocol (Brooks *et al.,* 1977) before and after each experiment.

In experiment I (Papers I–II), the SWc pigs (Batch 1) were fed according to Swedish feeding norms and the average animal weight during the test period (3 d) was 113 kg (SD 8 kg). In experiment II (Paper III–IV) the CWc and CWr pigs (Batch 2) were fed at 75% of the feeding norm and the average animal weight during the test period (4 d) was 101 kg (SD 18 kg) in Paper III and 98 kg (SD 18 kg) in Paper IV.

Experimental set-up

The test area consisted of two rectangular pens with a test aisle in between. The floor of the test aisle was covered by replaceable floors. Pig gait on the test aisle was recorded by a built-in force plate (FP) level with the paved surface and a perpendicularly placed digital video (DV) camera. Temperature and humidity were recorded by a data logger during the test period.

In experiment I (Papers I and II) the test aisle was a straight line (Figure 6), while in experiment II (Papers III and IV) the test aisle had a 30° curve just after the FP (Figure 7).

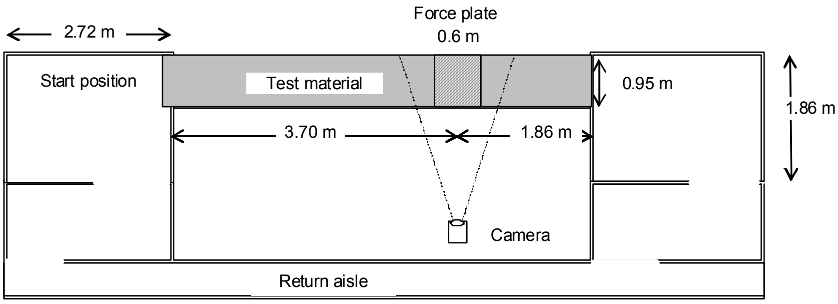

Figure 6. Plan of the test aisle used in experiment I (Paper I, II) for pigs walking a line.

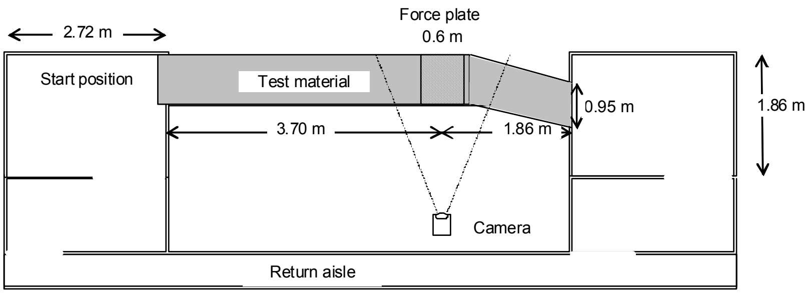

Figure 7. Plan of the test aisle used in experiment II (Papers III, IV) for pigs walking a curve.

Floor conditions

The flooring material used in Papers I-III was solid concrete slabs (right picture in Figure 8), representing flooring properties typical for commercial pig facilities. The surface finish was created 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.

In Paper IV the test aisle was covered by 20 mm thick rubber mat (KEN® Gummiwerk Kraiburg Elastik, Germany) with a rubber-studded underside profile (left picture in Figure 8).

In each set-up the clean floor conditions were tested first and then the fouled floor conditions (Figure 9). The test floor was fouled in a standardised way using pig faeces (approx. 1.5 kg/m^2) and the total dry matter content of each batch of faeces used to foul the test aisle was recorded.

Figure 8. Clean rubber floor mat KEN® (left) and concrete flooring (right) used in Paper IV.

Figure 9. Fouled rubber floor mat KEN® (left) and SRT friction measurement device on FP flooring (right).

Experiments

The pigs walked the test aisle individually at a self-chosen speed. The number of passages for each pig was 10 per replicate. Two replicates were conducted for each floor condition. A successful passage by a 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 experiment I, DV data were collected at 25 Hz, VGA quality with 640 x 480 pixels of the moving pigs, which captured 1.3-1.5 m of a pig body length (average 1.4 m) in the camera viewer. In experiment II, DV data were collected at 60 Hz by an IEEE 1394 camera with 656 x 490 pixels in 2.3 m of the test aisle.

The camera was spatially calibrated using a rectangle of known dimensions placed in the central path of the test aisle before each replicate.

After the experiment each film was imported and processed in a gait analysis programme (Vicon, Peak Motus 9.0, UK) in which the films were cut and digitised. Five positions of the animal were digitised in each DV frame: the four claw tip positions and either nose tip or tail root position. The nose tip/tail root position of the animal was 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 under Abbreviations and terms.

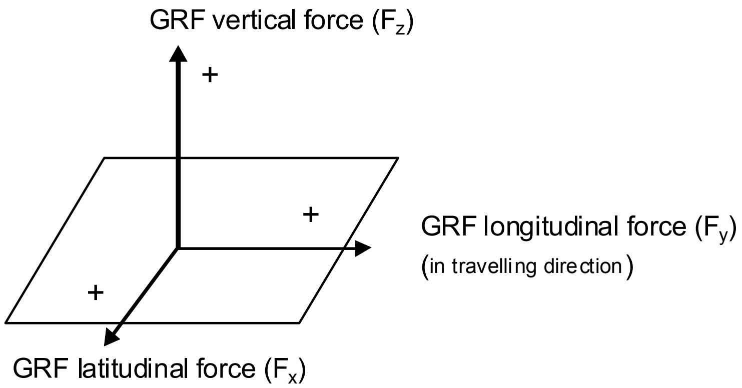

Figure 10. The force plate coordinate system, with force directions shown as reaction oriented forces.

GRF data were collected during the passage of the moving pigs at 1 kHz using an FP. The test aisle and the FP were covered with the same concrete or rubber mat flooring material. The GRF data acquisition system consisted of an FP (Bertec Corporation, Ohio, USA), connected to a digital converter and a computer. Three GRFs (GRF_v and the horizontal components GRF_{long} and GRF_{lat}) were recorded by the FP (Figure 10).

Coefficient of friction

Prior to the experiments, floor friction assessments were made by two different test devices, a horizontal pull slip meter (PSM) designed at the Department of Rural Buildings (Figure 11) and an SRT dynamic pendulum impact-type tester (ASTM, 1993). During the experiments the SRT was used for floor friction assessments after the last pig replica.

Figure 11. The PSM friction measurement device (at FP calibration set-up).

According to a Shore testing meter, the pig claw heel bulbs had a hardness of 30-35° Shore A. To reflect the conditions at the claw and floor interface during actual slip (Chang *et al.*, 2001a), the test body of both the PSM and SRT 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).

The contact area of the sliding body of the PSM corresponded to a claw area of 0.002 m^2 in accordance with Baxter (1984) and a pig weight of 61 kg, which was also used as the normal force. The test body was pulled horizontally along the floor by a hydraulic piston and the force required to pull it was recorded by a load cell placed between the test body and the piston. The ratio between the pulling force and total vertical (normal) force was calculated as the peak SCOF, occurring at the moment the body was set in motion, and as DCOF, the mean during a distance of 0.15 m. A mean of 10 runs was calculated on different locations for each type of floor conditions for SCOF and DCOF respectively.

The SRT (Figure 9) measures the friction when a slider edge, positioned at the end of a pendulum, is propelled over the test surface. The values obtained, British Pendulum Number (BPN), represent the frictional properties. The greater the friction, the more the swing is retarded, and the larger the BPN reading.

Immediately after the last pig replicate, five swings of the pendulum were made at three random locations on the floor surface covering the FP according to ASTM (1993). The BPN was expressed as the mean of the 15 values obtained. For comparison, the SRT was also run over the surface conditions tested with its original rubber test body.

Data processing

Two dimensional (2D) coordinates were constructed by direct linear transformation in the gait analysis programme, from which 2D velocity and 2D coordinates were imported into an Excel spreadsheet for further processing.

The kinetic data were obtained by sampling the GRF data in 300 evenly distributed values during the stance phase. The 300 values corresponded to the mean stance phase length. Sampling was performed in three force directions using the vertical force curve as a template. All GRF data were normalised to pig body weight.

A mean value per pig and type of surface conditions was compiled for each of the 300 sampling points and a mean and peak value were calculated for 10 pigs per floor condition type.

The claw force data were processed to determine the ratio of horizontal to normal forces (UCOF), which was calculated as a mean of peak UCOF during stance time for 10 pigs per floor condition. The UCOF data were screened for spurious values and values less than 10% of the peak vertical force were discarded. These originated from small vertical force values during claw-on and claw-off. Because of division by small numbers in the UCOF ratio, these peak UCOF values showed false maxima (Cham and Redfern, 2002a; Powers *et al.*, 2002).

The number of slips as well as slip length and slip time was registered for each passage. The slips were divided into forward and backward slips. A slip below a threshold of 10 mm was referred to as micro-slip and was disregarded, whereas a slip above the threshold was characterised as a slip from which the subject recovered or did not recover (Perkins, 1978; Applegate *et al.*, 1988; Cham and Redfern, 2002b). Slip frequency was defined as the number of slips in relation to the total number of stances per pig and limb.

Statistical analysis

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

Summary of results

Pigs walking a straight line on concrete

Kinematics

Gait differences due to floor conditions

On clean floors, SWc pigs had an unprovoked four-beat symmetrical gait with alternating 2- and 3-limb support phases and a high rate of diagonality (Table 4).

Table 4. *Kinematic parameters from the floor conditions and limbs of SWc pigs. Comparison between fore and hind limbs and between clean and fouled concrete floor conditions (10 readings per pig and floor condition, mean and standard deviation (SD))*

Parameter	Condition			Limb[2]		
	Clean	Fouled	p[1]	Fore	Hind	p[1]
Walking speed, m/s	1.65 (0.13)	1.31 (0.19)	⋆⋆⋆			
Stride length, m	0.86 (0.11)	0.72 (0.12)	⋆⋆⋆			
Swing/stance phase ratio	0.90 (0.09)	0.84 (0.14)	ns	0.81 (0.10)	0.93 (0.11)	⋆⋆⋆
Stance time, s	0.27 (0.02)	0.32 (0.04)	⋆⋆	0.31 (0.05)	0.28 (0.05)	⋆

[1)] Probability limits for statistical significance: ns = non-significant; ⋆ = p<0.05; ⋆⋆ = p<0.01; ⋆⋆⋆ = p<0.001

[2)] Fore and hind limbs on clean and fouled conditions

Pigs altered their gait to fouled floor conditions by reducing walking speed, lowering diagonality and employing more 3-limb support phases. A change in gait pattern took place from a clear DS walk in clean floor conditions to a mix of DS and LS walk in fouled floor conditions (Figure 12). Pigs also shortened their stride length and prolonged their stance time.

Gait differences between fore and hind limbs

The pig fore limbs differed from the hind limbs, with a lower swing/stance time ratio but longer stance time in both floor conditions (Table 4).

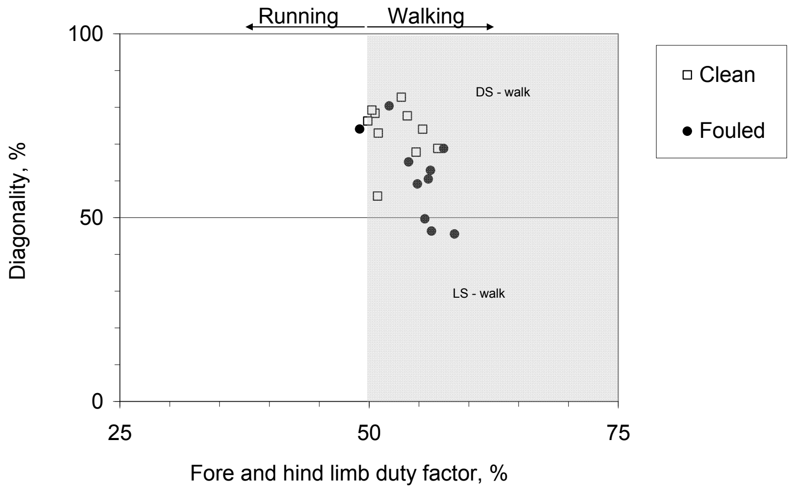

Figure 12. Hildebrand diagram of diagonality against mean duty factor for symmetrical gaits in SWc pigs. Open squares represent gait cycles on clean test aisle; solid circles represent cycles on fouled test aisle. The lower right area of the diagram represents LS walking gaits and the upper right area DS walking gaits, adapted from Lemelin *et al.* (2003).

Kinetics

Mean vertical and horizontal force curves exerted by fore and hind limbs on the FP from 10 pigs walking a straight line are illustrated in Figure 13. The vertical force showed two local maxima with a minimum in between.

The longitudinal horizontal force roughly described a sinusoidal curve, with a negative maximum illustrating backward forces acting on the claw followed by a positive maximum with forward forces acting on the claw.

The lateral horizontal force was less consistent and varied between fore and hind limbs, but was mainly negative during the stance phase, which meant that the claw had an outward thrust in the lateral direction.

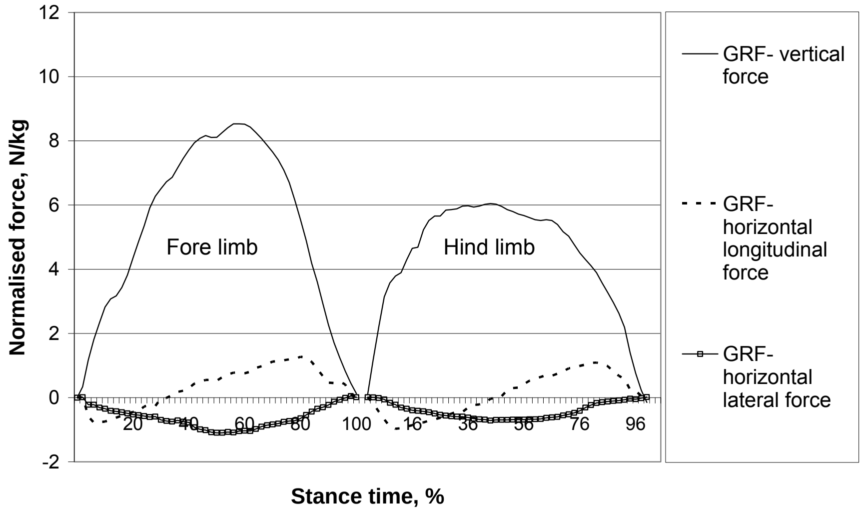

Figure 13. Normalised GRF exerted by fore and hind limbs during stance phase from 10 SWc pigs walking a line. Values derived from force plate measurements on clean concrete.

Gait differences due to floor conditions

The SWc pigs changed their gait in fouled surface conditions, resulting in significant differences in gait biomechanics compared with clean concrete surface conditions (Figures 15-24). The peak GRF_v applied was higher and the time of peak vertical force occurred earlier for SWc fore limbs than hind limbs on the clean floor than on the fouled floor. The minimum GRF_{long} applied in fouled floor conditions decreased for both fore and hind limbs compared with clean floor conditions. For minimum GRF_{lat} and peak GRF_{long}, the decrease on the fouled floor was significant for fore and hind limbs, respectively.

The highest peak UCOF occurred at claw-on and claw-off, with a minimum at the mid-stance phase for both fore and hind limbs in both types of floor conditions. Peak UCOF of both fore and hind limbs decreased in fouled floor conditions compared with clean for pigs walking a straight line (Figure 21).

Gait differences between fore and hind limbs

For both type of surface conditions, the mean GRF_v and the peak GRF_v applied by fore limbs were higher than the force exerted by hind limbs (Figures 15, 16). The time of peak GRF_v occurred later for fore limbs compared with hind limbs in both types of floor conditions.

The peak GRF_{long} was lower for fore limbs than for hind limbs in both types of floor conditions, but no difference was found for the peak lateral horizontal force. Minimum GRF_{long} and minimum GRF_{lat} applied by fore limbs were only lower than for hind limbs on clean concrete. As for peak UCOF, there were no differences between fore and hind limbs in any type of floor conditions (Figures 17-21).

Floor friction

With the PSM testing device, both SCOF and DCOF were significantly higher in clean than fouled floor conditions (Figure 22). Corresponding differences were also found for SRT leather and SRT rubber (Figure 23).

Pigs walking a curve on concrete

Kinematics

Gait differences due to floor conditions

In both floor conditions the CWc pig walk was characterised by a four-beat symmetric gait distinguished by alternating 2- or 3-limb support phases. When walking a curve on fouled concrete, the pigs reduced their walking speed and stride length by 9%, used a higher number of 3-limb support phases and lower diagonality (Figure 14, Table 5). The other stride parameters showed no differences between floor conditions.

Table 5. *Kinematic parameters from the floor conditions and limbs of CWc pigs. Comparison between fore and hind limbs and between clean and fouled concrete floor conditions (10 readings per pig and floor condition, mean and standard deviation (SD))*

Parameter	Condition			Limb[2]		
	Clean	Fouled	p[1]	Fore	Hind	p[1]
Walking speed, m/s	1.10 (0.17)	1.00 (0.19)	*			
Stride length, m	0.95 (0.06)	0.86 (0.06)	***			
Swing/stance phase ratio	0.90 (0.12)	0.89 (0.17)	ns	0.93 (0.15)	0.86 (0.14)	**
Stance time, s	0.47 (0.12)	0.48 (0.12)	ns	0.46 (0.11)	0.49 (0.12)	**

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

2) Fore and hind limbs on clean and fouled conditions

Gait differences between fore and hind limbs

The CWc hind limbs differed kinematically from the fore limbs, with a lower swing-stance time ratio and higher stance time than the fore limbs.

Gait differences due to floor conditions

Both mean and peak GRF_v applied decreased by 5 and 15% for CWc fore and hind limbs, respectively, in fouled floor conditions (Figures 15, 16) and peak vertical force occurred 13% later than mid-stance (half-stance time) compared with clean (8%) for fore limbs.

In fouled floor conditions the peak GRF_{long} (propulsion force) was 45 and 32% lower and the minimum GRF_{long} (braking force) applied by the CWc pigs was 75 and 57% higher for fore and hind limbs, respectively, compared with clean floor conditions. The GRF_{lat} and UCOF showed no differences between floor conditions (Figures 17-21).

Gait differences between fore and hind limbs

The CWc hind limbs differed from the fore limbs, with lower mean and peak GRF_v in both floor conditions.

The peak GRF_{long} was 50 and 60% lower for fore limbs than for hind limbs in both clean and fouled floor conditions, while in fouled floor conditions the peak GRF_{lat} of fore limbs exceeded that of hind limbs. In clean floor conditions fore limbs utilised 48% more minimum GRF_{long} than hind limbs, whereas in fouled floor conditions the fore limb braking force increased to 65% more than that utilised in hind limbs.

The minimum GRF_{lat} (outward correction force) applied by fore limbs was 2.3 and 1.5 times higher than for hind limbs in clean and fouled floor conditions, respectively. Regarding peak UCOF, there were no differences between fore and hind limbs in either of the floor conditions.

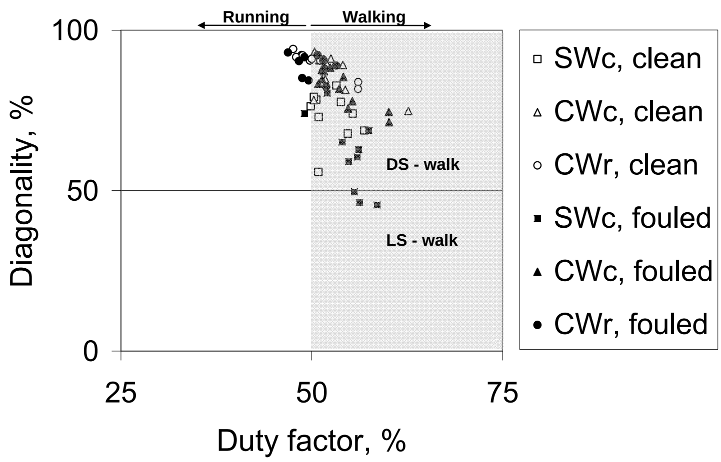

Figure 14. Hildebrand diagram of diagonality against mean duty factor for symmetrical gaits in SWc, CWc and CWr pigs. Open squares, triangles and circles represent gait cycles on clean test aisle; solid squares, triangles and circles represent cycles on fouled test aisle. The lower right area of the diagram represents LS walking gaits and the upper right area DS walking gaits, adapted from Lemelin *et al.* (2003).

Floor friction and slip

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 (Figures 22, 23).

Backward and forward slip lengths were of the same order of magnitude and the backward and forward slip frequency was constant for hind limbs. However, for fore limbs the forward slip frequency was more than double the backward slip frequency. In clean floor conditions no slips >10 mm were observed (Figure 24).

Pigs walking a curve on rubber mat

Kinematics

Gait differences due to floor conditions

With a curve walking speed of 1.18 m/s in clean floor conditions and 1.06 m/s in fouled floor conditions, the CWr pig walk 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 (Figure 14).

For CWr pigs in fouled floor conditions compared with clean, swing, stance and stride time and number of 3-limb support phases increased by approx. 10%.

Gait differences between fore and hind limbs

The CWr pig fore limbs showed significantly higher swing/stance time ratio and lower stance time than hind limbs, but consistent stride elevation in the two types of floor conditions.

Kinetics

Gait differences due to floor conditions

Both mean and peak GRF_v applied decreased by 10 and 20% for fore and hind limbs, respectively, in fouled floor conditions (Figures 15, 16), while time of peak vertical force for fore limbs occurred 8% later than mid-stance (half-stance time) compared with 6% for clean conditions. The hind limbs used mid-stance for full vertical force in clean floor conditions, but in fouled floor conditions the CWr hind limbs applied full force 5% earlier than mid-stance.

The minimum GRF_{long} (braking force) and the peak GRF_{long} (propulsion force) showed no difference in either fore or hind limbs in clean and fouled 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 (Figures 17-21).

Gait differences between fore and hind limbs

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.

The peak GRF_{long} was 43 and 63% lower for fore limbs than for hind limbs in clean and fouled floor conditions, respectively. In fouled floor conditions the peak GRF_{lat} of fore limbs was double that of hind limbs. In clean floor conditions, fore limbs utilised 26% more minimum GRF_{long} than hind limbs, whereas in fouled floor conditions this difference in braking force increased to 39%. The minimum GRF_{lat} 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.

Floor friction and slip

Significant differences in SCOF and DCOF were found between clean and fouled floor conditions for PSM leather, SRT leather and SRT rubber (Figures 22, 23).

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 (Figure 24).

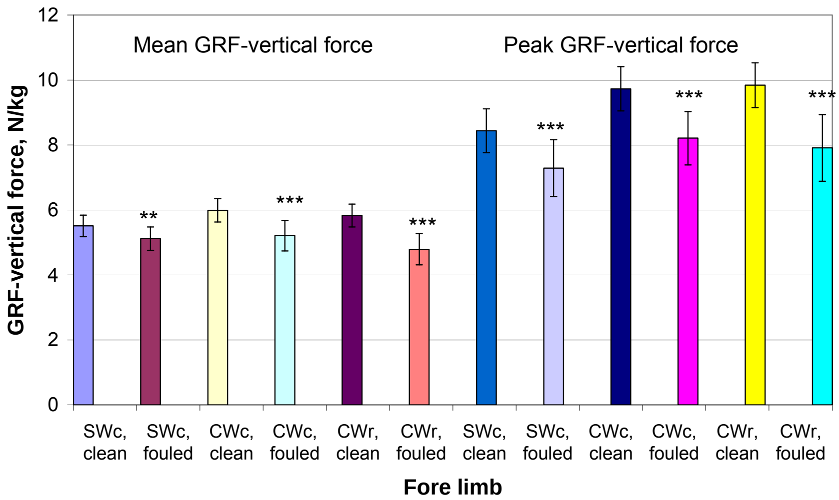

Figure 15. GRF_v forces reflecting changes in gait in fore limbs from pigs walking a line on concrete (SWc), walking in a curve on concrete (CWc) and walking in a curve on rubber mat (CWr), in clean and fouled floor conditions. Values are means from 10 pigs and error bars are SD. Asterisks indicate significant differences between clean and fouled floor conditions.

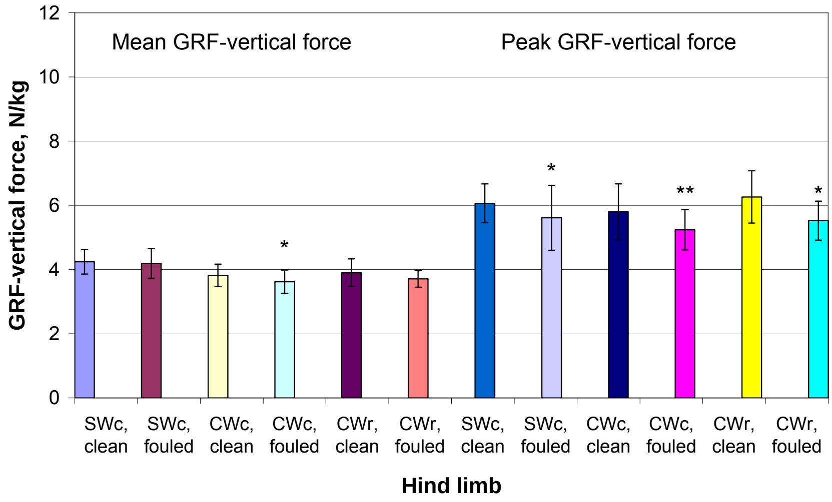

Figure 16. GRF$_v$ forces reflecting changes in gait in hind limbs from pigs walking a line on concrete (SWc), walking in a curve on concrete (CWc) and walking in a curve on rubber mat (CWr), in clean and fouled floor conditions. Values are means from 10 pigs and error bars are SD. Asterisks indicate significant differences between clean and fouled floor conditions.

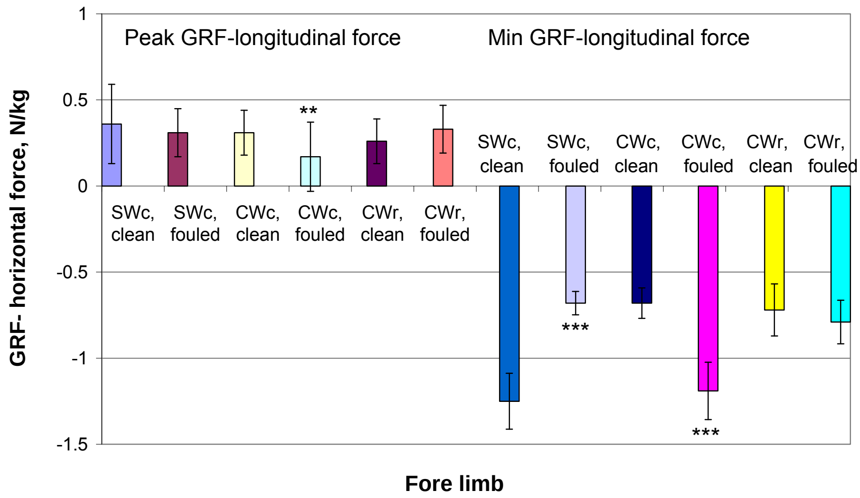

Figure 17. Peak and minimum GRF$_{long}$, propulsion and braking forces reflecting changes in gait in fore limbs from pigs walking a line on concrete (SWc), walking in a curve on concrete (CWc) and walking in a curve on rubber mat (CWr), in clean and fouled floor conditions. Values are means from 10 pigs and error bars are SD. Asterisks indicate significant differences between clean and fouled floor conditions.

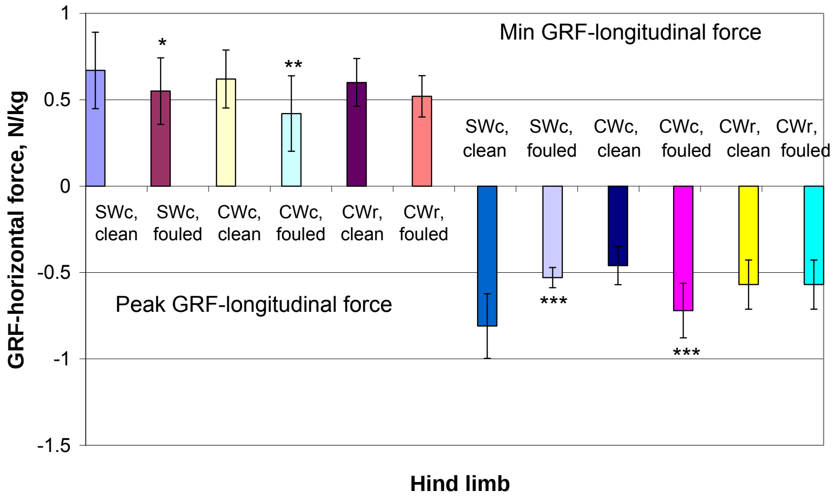

Figure 18. Peak and minimum GRF_{long}, propulsion and braking forces reflecting changes in gait in hind limbs from pigs walking a line on concrete (SWc), walking in a curve on concrete (CWc) and walking in a curve on rubber mat (CWr), in clean and fouled floor conditions. Values are means from 10 pigs and error bars are SD. Asterisks indicate significant differences between clean and fouled floor conditions.

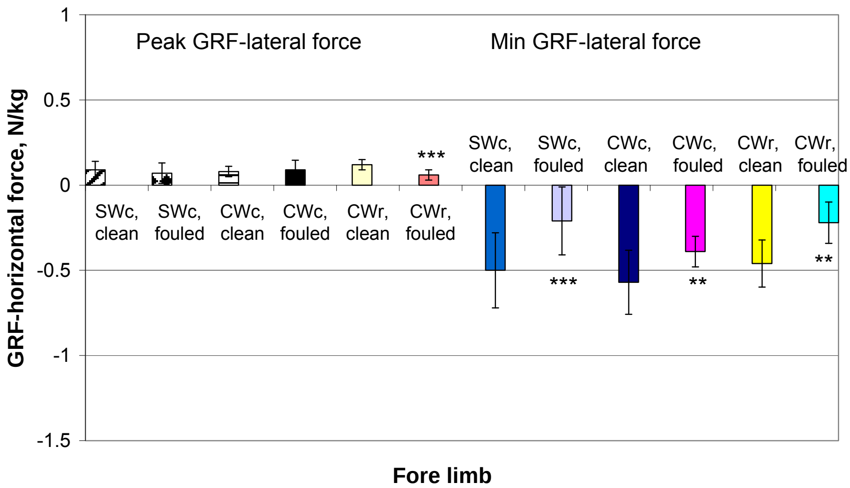

Figure 19. Peak and minimum GRF_{lat}, inward and outward acting forces reflecting changes in gait in fore limbs from pigs walking a line on concrete (SWc), walking in a curve on concrete (CWc) and walking in a curve on rubber mat (CWr), in clean and fouled floor conditions. Values are means from 10 pigs and error bars are SD. Asterisks indicate significant differences between clean and fouled floor conditions.

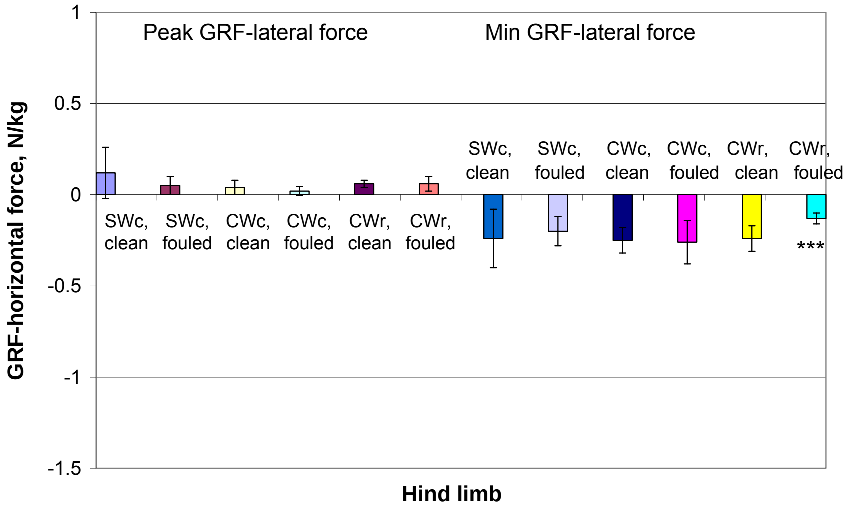

Figure 20. Peak and minimum GRF_{lat}, inward and outward acting forces reflecting changes in gait in hind limbs from pigs walking a line on concrete (SWc), walking in a curve on concrete (CWc) and walking in a curve on rubber mat (CWr), in clean and fouled floor conditions. Values are means from 10 pigs and error bars are SD. Asterisks indicate significant differences between clean and fouled floor conditions.

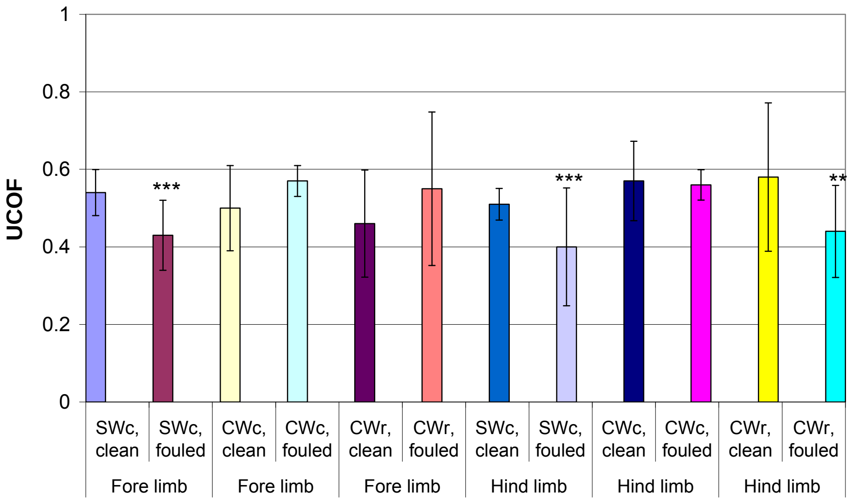

Figure 21. UCOF reflecting changes in gait in fore and hind limbs from pigs walking a line on concrete (SWc), walking in a curve on concrete (CWc) and walking in a curve on rubber mat (CWr), in clean and fouled floor conditions. Values are means from 10 pigs and error bars are SD. Asterisks indicate significant differences between clean and fouled floor conditions.

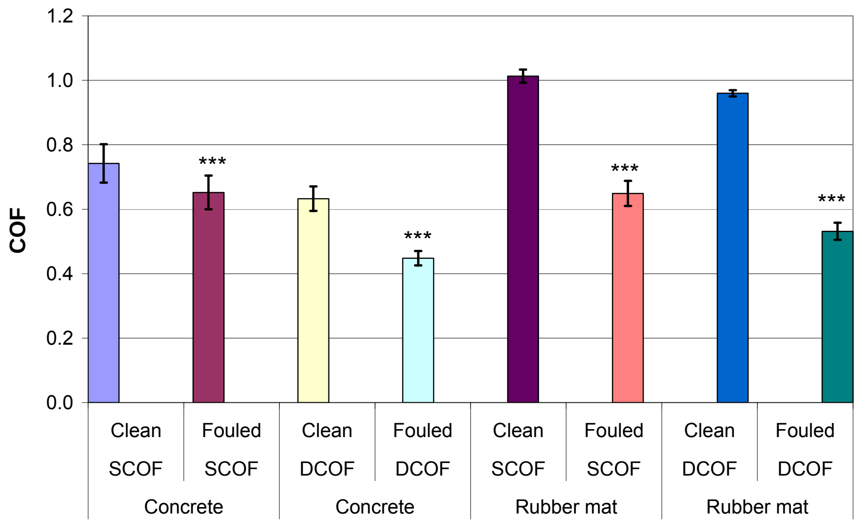

Figure 22. Static (SCOF) and dynamic (DCOF) coefficient of friction for clean and fouled conditions of concrete and rubber mat, tested in the laboratory. Values are means from 10 pigs and error bars are SD. Asterisks indicate significant differences between clean and fouled floor conditions.

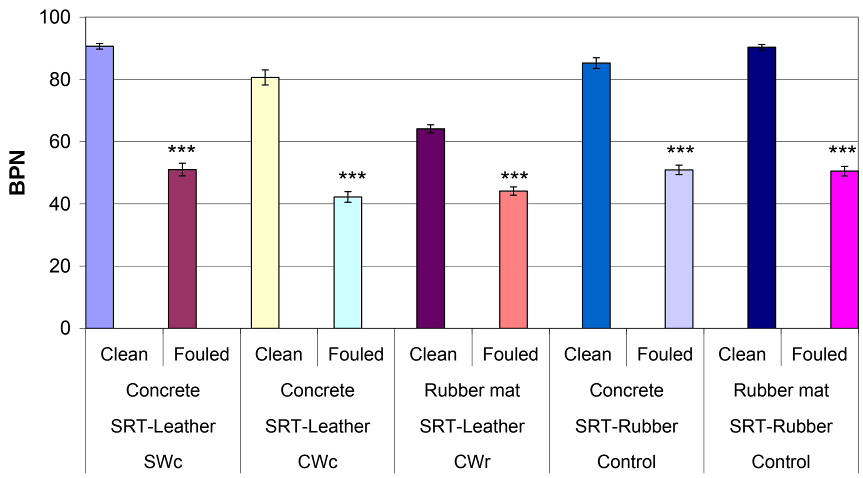

Figure 23. BPN for SWc and CWc pigs in clean and fouled conditions of concrete and CWr pigs on rubber mat, tested both in pig house experiments and laboratory (control). Values are means from 10 pigs and error bars are SD. Asterisks indicate significant differences between clean and fouled floor conditions.

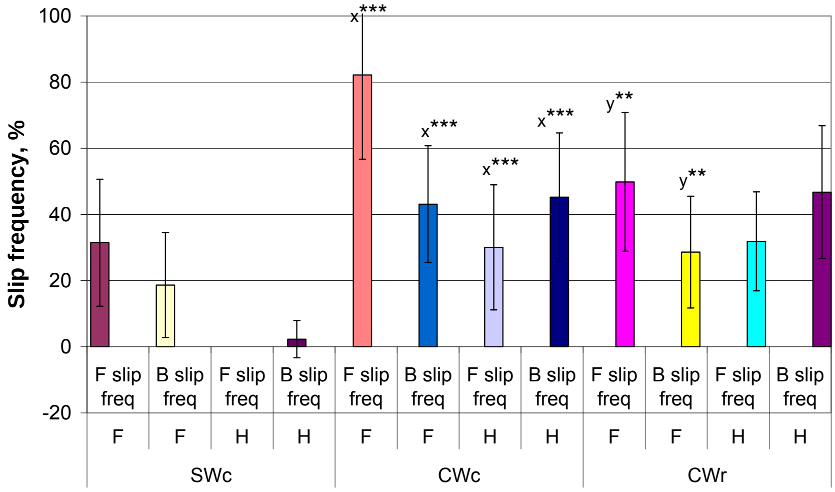

Figure 24. Fore (F) and hind (H) limb forward (F slip freq) and backward slip frequency (B slip freq) from pigs walking a line on concrete (SWc), walking in a curve on concrete (CWc) and walking in a curve on rubber mat (CWr) in fouled floor conditions. Values are means from 10 pigs and error bars are SD. x indicates a significant difference between SWc and CWc pigs, and y indicates a significant difference between CWc and CWr pigs.

Discussion

Gait parameters

Kinematics

In these studies we attempted to describe pig walk in common situations with different flooring conditions, but in a rather strict way. The pigs used in the experiments were chosen from a commercial pig race with healthy feet and gait.

The symmetrical walking pattern with 2- and 3-limb support phases exhibited at slow speeds by SWc, CWc and CWr pigs has also been found in other mammals, *e.g.* dogs, sheep, horses, cattle and pigs (Hildebrand, 1965; Jayes and Alexander, 1978; Hottinger *et al.*, 1996; Hodson *et al.*, 2001; Flower *et al.*, 2005; Thorup *et al.*, 2007). The symmetrical walk signifies a longer stance than swing time with a duty factor and diagonality >50, *i.e.* a DS-LS walk.

The average speed of the SWc pigs was somewhat higher, although the walking speed, stride length and stance time in clean floor conditions for CWc and CWr pigs correspond well with data from dogs and pigs (Calabotta *et al.*, 1982; Hottinger *et al.*, 1996; Thorup *et al.*, 2007).

Kinetics

In limb-floor interaction, it is the two toes of each limb in a pig that carry the weight and that make contact with the floor at toe-on. In motion, the pig GRF_v force curve shows two local maxima with a minimum in between for both fore and hind limbs. However the twin GRF peaks observed in SWc pigs were not as evident as those reported by Thorup *et al.* (2007), probably due to higher walking speed in our study, 1.65 m/s compared with 0.88 m/s.

The longitudinal GRF force roughly described a sinusoidal curve, with a negative maximum illustrating braking forces acting on the claw followed by a positive maximum of propulsive forces acting on the claw during the stance phase. The horizontal GRFs (GRF_{long} and GRF_{lat}) were much smaller, approx. 20 and 10% respectively of the GRF_v force.

The GRF time course of the pigs in the present study was in range of those reported for dogs, horses and pigs (Hottinger *et al.*, 1996; Hodson *et al.*, 2001; Khumsap *et al.*, 2002; Thorup *et al.*, 2007), although the range of GRF_v forces (5-8.5 N/kg) was higher than in those studies, probably due to body size and walking speed.

Methodology

The accuracy of a force plate analysis is largely determined by the subject's walking speed and associated stride length and stance time (Khumsap *et al.*, 2002). McLaughlin *et al.* (1996) concluded that all variation in subject velocity should be minimised in performing force plate analysis in horses. In dogs, the recommended variation should be less than 0.6 m/s at the walk (Roush and McLaughlin, 1994; Tano *et al.*, 1998). In laboratory measurements on humans, self-chosen gait speeds have ranged from 0.97 to 1.51 m/s (Redfern *et al.*, 2001; Abel *et al.*, 2002). The standard deviations of GRF forces in the present study were somewhat higher but of same order of magnitude as those in other studies (Hodson *et al.*, 2001; van der Tol *et al.*, 2005; Thorup *et al.*, 2007).

The experimental design in Papers I-IV was not fully randomised in the pig walking order in different floor conditions, since clean floor conditions were followed by fouled floor conditions for practical reasons, which also made the order of replicates non-randomised. The positive effect was that pig growth was limited between tests in clean and fouled floor conditions on a floor material.

The aspect of floor background limited the supply of pigs in the right range of weight, which could have influenced the variation, both in kinematic and kinetic analysis. The results derived in this study are based on animals that have a body weight of approx. 100 kg. This is the finishing weight of slaughter pigs and of newly pregnant gilts. The pigs used as models in this study could belong to either group. In slaughter pigs of approx. 100 kg, the sex affects some leg problems according to Jørgensen (2003), but this never became apparent in this study.

Gait differences between fore and hind limbs

Differences in fore and hind limb during the gait cycle became evident in the results from the pigs walking a straight line and a curve. In particular, the increased weight distribution on CWc fore limbs and longer stance time in fore limbs than hind limbs for SWc pigs, but the opposite for CWc and CWr pigs, implies that fore and hind limbs have different functions during gait.

Differences in other aspects such as the time course of peak GRF_v, propulsion and braking forces also point in the same direction. These differences could have implications on how vulnerable the limbs are to slipping accidents (Applegate *et al.*, 1988), irregularities in the floor surfaces, *etc.* (Jørgensen, 2003).

Gait differences in pig walk due to floor conditions

Kinematics

Both SWc and CWc pigs altered their gait to fouled floor conditions by reducing walking speed, shortening stride length and lowering diagonality and employing more 3-limb support phases. Furthermore, SWc and CWr pigs prolonged their stance time.

Comparable gait adaptations have been reported in studies of humans walking a line (Cham and Redfern, 2002a), cows (Phillips and Morris, 2000; Telezhenko and Bergsten, 2005; Jungbluth *et al.*, 2003) pigs (Thorup *et al.*, 2007) and humans descending stairs (Cham and Redfern, 2002b).

Applegate *et al.* (1988) noted that stride length, walking speed, time and phase were influenced marginally and inconsistently by differences between wetted test surfaces. 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 gait adaptation to fouled floor conditions by CWr pigs significantly differed from that of CWc pigs in higher stride length, diagonality and lower duty factor. Both CWc and CWr pigs prolonged their hind stance phase compared with pigs walking a line (Applegate *et al.*, 1988; Thorup *et al.*, 2007), 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).

The CWr pig stride data and the Hildebrand diagram (Figure 14) show that the pigs found a moderate gait adaptation to the fouled surface to be sufficient to cope with the fouled and curved rubber flooring surface. The reluctance of CWr pigs to make further gait adaptations could have been due to the firmer foot grip from the rubber matting in fouled floor conditions (Benz, 2002; Telezhenko and Bergsten, 2005; Reubold, 2008).

Kinetics

A major effort was made by the pigs observed in our studies to reduce walking speed and thus the vertical and, more importantly, the horizontal forces, in their gait adaptation to fouled floor conditions. With reduced vertical and horizontal forces there is a reduction in UCOF when the available friction from the fouled floor surface decreases, which lowers the probability of slipping.

GRF vertical force

The effect of this adaptation was seen in SWc, CWc and CWr pigs, where the mean and peak GRFv were reduced in fouled floor conditions, except in hind limbs for SWc and CWr pigs (Figures 15, 16). This reduction was also observed by Thorup *et al.* (2007).

The CWc pigs increased their body weight on the fore limbs by 5% in clean floor conditions compared with SWc pigs and pigs in the Thorup *et al.* (2007) study, but also compared with CWr pigs. In fouled floor conditions the CWc hind mean GRF_v was lower than in SWc (no centripetal force), which could mean that weight was transferred to the fore limbs.

Horizontal GRF longitudinal force

In SWc, CWc and CWr pigs, the peak horizontal GRF_{long} (propulsion force) from the hind limbs was approx. twice as large as that from the fore limbs in both clean and fouled floor conditions. This was not observed by Thorup *et al.* (2007), probably as a result of higher walking speed and body weight. On fouled floors the propulsion force for SWc pigs was lowered by approx. 15% for both limbs, in agreement with Thorup *et al.* (2007).

The CWc pigs reduced their propulsion force in fore and hind limbs in fouled floor conditions. In contrast, the higher propulsion force in CWr pig fore limbs in fouled floor conditions revealed better traction compared with

CWc pigs and the propulsion values corresponded to the findings from SWc pigs.

However, the CWr pig propulsion force was approx. 50% lower than the propulsion force of fore and hind limbs in fouled floor conditions reported by Thorup *et al.* (2007). This difference in propulsion force was even larger for SWc and CWc pigs. The discrepancy may be attributable to differences in floor surface condition.

For SWc pigs the minimum horizontal GRF_{long} (braking force) of the hind limbs was reduced to the same level as in the fore limbs in fouled floor conditions, confirming findings by Thorup *et al.* (2007). The CWc pigs increased the braking force in both limbs in fouled floor conditions to the braking force level of SWc pigs in clean floor conditions.

Compared with CWc pigs, the CWr pigs used a consistent amount of braking force in both limbs in both floor conditions. 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 rubber floor surface.

The CWr pig fore limb braking force values in both clean and fouled floor conditions were consistent with values reported for pigs walking a straight line on concrete (Thorup *et al.*, 2007), further implying that CWr pigs had a firm foot grip. The braking forces for CWr hind limbs in clean and fouled floor conditions were lower than reported for pigs walking a straight line on concrete (Thorup *et al.*, 2007). In CWc and CWr the braking force was produced by both limbs, but mainly by the fore limbs as in SWc pigs. The difference in braking force values for SWc, CWc and CWr compared with Thorup *et al.* (2007) are probably due to higher pig body weight and walking speed.

Horizontal GRF lateral force

Changes in peak and minimum horizontal GRF_{lat} (inward and outward stabilisation forces) predominantly occurred in fore limbs in fouled floor conditions. For SWc pigs the outward correction force in clean floor conditions was larger for fore limbs than for hind, and resulted in a 60% reduction for fore limbs on fouled floors compared with clean. The reduced correction, not significantly inward, indicates that in fouled floor conditions pigs choose to restrict the lateral stabilising forces in order to gain stability, which confirms the results of Thorup *et al.* (2007).

However, in fouled floor conditions the CWc pigs increased their stabilisation efforts for fore limbs compared with SWc pigs. 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.

Utilised coefficient of friction, UCOF

The mean peak UCOF value for SWc pigs was 0.54 and 0.43 for fore limbs and 0.51 and 0.40 for hind limbs in clean and fouled floor conditions respectively, as the ratio of horizontal and vertical GRF. The peak UCOF reduction in both limbs of SWc pigs was mainly due to the reduction in horizontal forces, again owing to a reduction in walking speed in fouled floor conditions (Powers *et al.*, 2002; Cham and Redfern, 2002a; Thorup *et al.*, 2007).

The comparable peak UCOF value obtained in tests on humans in dry floor conditions is approx. 0.20 (McVay and Redfern, 1994; Burnfield *et al.*, 2005). For cows walking a straight line on dry, level floors, the peak UCOF value is reported to be 0.54 (van der Tol *et al.*, 2005) and for pigs walking a straight line 0.48 and 0.32 (both limbs) in dry and greasy floor conditions, respectively (Thorup *et al.*, 2007).

The CWc gait adaptation to fouled floor conditions produced lower vertical forces, a twofold reduction in propulsion and outward stabilisation force and a threefold increase in braking force, without reducing the peak UCOF. The CWc pigs used more braking force than SWc pigs in fouled floor conditions. Thus the peak UCOF values for both limbs of the CWc pigs exceeded the recorded DCOF and the corresponding values of SWc found under fouled floor conditions.

Burnfield *et al.* (2005) discovered that humans had a mean peak UCOF of 0.48 negotiating a 90° turn, while van der Tol *et al.* (2005) found that peak UCOF for cows walking a 90° curve (FP placed in the middle of the curve) in dry floor conditions remained 0.40 during almost the entire stance phase and recorded a peak UCOF value of 0.80 during the heel strike phase in stopping tests.

The FP placement just before the curve could explain the high peak UCOF level during stance phase but also the high peak UCOF level at toe-on and toe-off compared with SWc pigs in Paper II and pigs in the Thorup *et al.* (2007) study.

The CWr pig gait adaptation to fouled floor conditions (Paper IV) produced a threefold reduction in lateral horizontal forces and kept braking and propulsion forces constant, resulting in a constant peak UCOF level in fore limbs but a 31% reduction in peak UCOF in hind limbs in fouled floor conditions. For the CWr pigs the better floor traction probably increased the floor friction and reduced the impact forces, creating the possibility of an appropriate but smaller gait adaptation (no stride length or diagonality reduction).

Floor friction and slip

Floor friction

Two friction testing devices were used to give more comparable data. The SRT device was chosen because of its dynamic impact-related friction value, which corresponds to the conditions at the claw and floor interface during slip (Chang *et al.*, 2001a). The test body of both the SRT and the horizontal PSM were covered by a piece of leather matching pig claw hardness and friction (Bring, 1964). The size of the PSM test body corresponded to a foot size of 61 kg pig, and the mean dynamic sliding speed of the test body was 0.02 m/s, which was probably too slow to be compatible with the walk of a pig.

When comparing the PSM DCOF with peak UCOF values of SWc pigs, the slip frequency in fouled floor conditions tells us that DCOF and peak UCOF values were very close in range and thus some slip, mainly forward slip, occurred. For the CWc pigs, the peak UCOF exceeded DCOF values in both fore and hind limbs, which can also be seen in high (forward and backward) slip frequencies.

For CWr pigs, the peak UCOF value of the fore limbs barely exceeded DCOF but hind limb peak UCOF values fell below DCOF. This could also be noted in a higher forward slip frequency in fore limbs than in hind limbs.

In comparing DCOF and corresponding peak UCOF values it is clear that in order for a slip measuring device to predict the slipperiness of a floor, it has to consider the foot loading rate as well as the dynamic sliding speed of the moving animal (Strandberg, 1983; Hanson *et al.*, 1999; Redfern *et al.*, 2001; Grönqvist *et al.*, 2001).

The SRT device has a dynamic impact, with a nearly constant contact force between the slider and the walking surface, but according to Grönqvist *et al.* (1999), the magnitude of normal force depends on the COF value. Non-impact measurement techniques used in the PSM friction measuring device may underestimate the actual risk of slipping and falling, particularly when wet, oily or greasy conditions are encountered (Chang *et al.*, 2001a).

COF measurements could be improved by incorporating foot loading rate and dynamic sliding speed of the moving subject into the friction measuring devices to achieve better correspondence with an animal walking situation (Grönqvist *et al.*, 2003b; Aschan *et al.*, 2005).

Slip

The risk of slipping forward was greatest in fore limbs, in agreement with Applegate *et al.* (1988), while the leading foot also uses the largest braking force and sets the walking direction (Redfern *et al.*, 2001). Applegate *et al.* (1988) also reported that the fore limbs of pigs at toe-on lie further from the body's centre of gravity than hind limbs, which would subject the fore limbs to more exposure to horizontal forces, resulting in more slips for fore limbs. The risk of slipping backwards is most likely for the limbs that have the highest propulsion force, *i.e.* the hind limbs. The CWc peak UCOF values and the slip frequencies in this thesis confirm these claims.

Applegate *et al.* (1988) found that forward slips in general were very small in both limbs. Small slips are often referred to as micro-slips (Redfern *et al.,* 2001) and occur without the knowledge of the 'walker'. Slip length and frequencies for SWc, CWc and CWr pigs were higher than found by Applegate *et al.* (1988), probably due to less friction. The COF and BPN values of fouled floor conditions for SWc and CWc pigs were considerably lower than any in the Applegate *et al.* (1988) study, but the PSM COF values fell almost within range of the COF values reported by Thorup *et al.* (2007).

The peak UCOF values for both limbs of the CWc pigs exceeded the recorded DCOF, which resulted in higher CWc forward and backward slip frequencies in both limbs as peak UCOF increased and the available friction from the fouled floor surface decreased (Hansson *et al.*, 1999).

The difference in CWc and CWr slip frequency could perhaps have an explanation in the 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 the deformation of the rubber flooring material. This deformation could provide additional friction, enabling the foot to sink into the floor to generate more traction (Nilsson, 1988; Reubold, 2008).

The peak UCOF values of CWc and CWr pigs are higher than the recommended COF values in the literature (Kovacs and Beer, 1979; Nilsson, 1988; Phillips and Morris, 2001). Thorup *et al.* (2007) suggested a minimum COF threshold of 0.63 to ensure walking safety on dry floor concrete surfaces.

The probability of slip and fall is determined not only by the shoe/foot, floor and degree of fouling, but also by the type of movement of the subject

(Hanson *et al.*, 1999). According to the results in this thesis, there is a high probability of finding high peak UCOF values associated with animal movements in a pen situation.

Conclusions

Research findings

The primary goal in modern pig production is to have as high productivity as possible in sow and finishing pig production. The production follows a strict plan, in which the producer decides the weaning period length, the pig genotype, the design of housing system in different parts of the production cycle, *etc*. This includes how and what diet the sows and growing pigs are fed and what type of flooring they are kept on. However, keeping pigs, particularly sows, healthy in legs and claws has been a persistent problem for producers. Closed production sites, with pigs born into a minimal disease environment, have not overcome the leg problems.

To address this problem, this thesis used the animal as an indicator of normal and adaptive gait to establish floor physical factors that better correspond to the biological needs of the pigs, in order to minimise the number of claw disorders that are directly linked to floor system.

The main findings in this thesis are as follows:

Hypothesis: Pig gait in different floor conditions can be characterised by a combination of kinematic and kinetic methods

- A data set of gait parameters was obtained that characterises the gait of pigs in clean and fouled floor conditions by a combination of kinematic and kinetic methods (Papers I, II).

Hypothesis: Pigs adapt their gait to fouled floor conditions when walking a straight line

- Pigs were shown to adapt their gait to fouled floor conditions when walking a straight line (Papers I, II).

Hypothesis: Pigs adapt their gait to walking a curve

- Pigs were shown to adapt to walking a curve in clean conditions but the pig gait adaptation was not enough for safe walking in fouled floor conditions, as peak UCOF exceeded DCOF in walking in a curve (Paper III).

Hypothesis: Pigs adapt their gait to a soft floor when walking a curve

- Pigs were shown to adapt to walking in a curve in clean conditions but the pig gait adaptation is not enough for safe walking in fouled floor conditions, as the peak UCOF of fore limbs barely exceeded DCOF in walking a curve (Paper IV).

Hypothesis: A soft floor improves walking safety for pigs walking a curve

- A soft floor material that increases floor friction forces at toe-on and toe-off in absorption of foot pressure can reduce the effect of horizontal forces at impact and with that reduce the risk of slipping, *i.e.* promote walking safety (Paper IV).

Additional findings:

- The UCOF data obtained for pig motion in walking a straight line and a curve can improve design criteria for pig floors (Papers II-IV).
- An improved friction measuring technique will give better agreement between UCOF and COF values (based on findings in Papers III, IV).

Research implications

Kinematic and kinetic methods proved to be reliable techniques for assessment of relevant gait parameters in characterising pig gait, using the subject as indicator in finding floor properties that better comply with the biological needs of the pig.

The fundamental gait parameters described by Hildebrand (1965) are important in characterising pig gait. Pig gait at walking follows the same pattern as other mammals and the parameters most affected by floor conditions are walking speed, number of limb support, diagonality, duty factor, peak GRF_v, min GRF_{long}, and peak UCOF.

A 30° curve is a safety hazard for pigs on fouled concrete. If the concrete surface has any irregularities and the pig has to pass through the curve a number of times every day, perhaps in competition with a number of other pigs, it is possible that a foot injury will occur, especially in the fore limbs.

Pigs feel more secure in their movements on rubber mat flooring, since they have a firmer foot grip in both clean and fouled floor conditions.

UCOF data from the experiment could be used in pen design and in pig housing systems. To date, there are no established design criteria for floor properties in pig houses. The peak UCOF values could be used as guiding values to determine required floor friction in different parts of a pig housing system.

Slip meters need to be improved to meet the demand of subject weight, impact at toe-on and subject foot speed at impact.

Practical implications

The quantitative non-invasive measurement technology used in this work is a useful tool but can probably only be used in laboratory experiments. Even so, it could provide validation data for instruments used in practice, *e.g.* a friction measurement device. This would allow the results to be applied at farm level.

With new knowledge of where, why and to what degree safety hazards can be found, *e.g.* in transporting/moving pigs within pig housing systems, precautions may be taken to prevent or reduce the risk of injury. Rubber mat material may also improve sow lying down behaviour, making farrowing pens safer both for sow and piglets. With new tools the pen designer can decrease the stress for pigs in pen situations in trying to reduce risky combinations such as a sloping, fouled floor with an elevated slatted dung area and a 90° bend.

In existing housing systems, combinations of measures can be taken to minimise safety hazards, *e.g.* deploying rubber mats where they are most needed, trying to reduce or eliminate fouled floors and surface cracks, increasing the frictional properties of the floor where competition is likely to erupt, reducing competition through choice of feeding system and, if possible, supplying straw bedding.

Future directions

When possible, the methodology of kinetics and kinematics would benefit from sampling two subsequent strides and using an additional camera to catch the sideway motion, making the sampled data more robust. More work is needed to verify the peak UCOF values that determine pig movements in a pen situation. With required data on subject foot weight and foot speed at impact COF values that better correspond to the biological needs of the animals can be determined in specific areas in farm buildings.

Rubber floor has hardly been tested as a flooring material for pig houses and questions remain on optimal rubber composition and degree of compressibility. Further research is needed before recommendations can be given.

Animal welfare considerations

The pigs used in experiments for Papers I-IV were examined in terms of feet and gait health according to a standard protocol by a veterinary surgeon before and after each experiment. In walking the fouled test aisles, the pigs were not subjected to more severe floor conditions than in ordinary pig pens. Permission to use research facilities and animals according to the experimental design was granted by the Swedish Board of Agriculture and the Central Animal Experimentation Board in 2003.

Acknowledgements

I want to express my sincere gratitude and appreciation to everyone who has contributed to this work. From research facilities, building and trying out a walkway for pigs to providing the money and the equipment and putting it all together in an experimental design, thank you all.

I am deeply grateful to my supervisors Christer Nilsson and Stefan Pinzke for all help, support and encouragement along with this work and special thanks to Stefan Pinzke for pushing for the first paper.

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

I want to express my special appreciation and gratitude to:
Evgenij Telezhenko in trying out the trackway analysing method on pigs,
The colleges of the Department of Anatomy, Physiology and Biochemistry, SLU for helping me with the FP installation,
Jan-Erik Englund for valuable experiment design and statistics counselling,
Andrus Kangro for mending my computers and helping me with new ones,
Pierre Kauhanen for saving my time with a GRF calculation macro,
Anders Prahl and Magnus Nilsson for building and trying out the test aisle,
A-Betong AB, Sweden; Stallmiljö i Dalby AB; Gummiwek Kraiburg Elastik Germany; Elmo Leather AB, Svenljunga for supplying materials,
Mats Olsson, Odarslöv, Bertil Larsson, Lackalänga for voluntary pigs,
Ingvar Johnsson for animal care and assisting in the experiment along with Linda, Magnus and Anders,
Carl-Johan Ehlorsson for claw and pig health recording,
Håkan Dragemark, Vägverket, Örebro for use of SRT measuring device,
Mary McAfee for language and spelling check, and being third supervisor,

and my enduring wife and family.

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