A Study of Slatted Concrete Floors in Sow Barns and Modelling of Sow Gait

by

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Abstract

Slatted concrete floors are commonly used in sow housing for ease of manure handling and durability. The floor configuration and properties may markedly affect animal welfare and health. This research investigated the slatted concrete floors in sow barns in terms of their performance in manure drainage, surface friction, and sow gait. In-barn tests were conducted to evaluate a slatted floor configuration which had 105 mm wide slats and 19 mm slots and was considered optimal by kinematic assessment for gestating sows. This was compared with the most commonly used configuration of 125 mm wide slats and 25 mm slots. Floors of the two configurations were installed in two sow gestation rooms which had the same climate conditions and stocking density. Digital images were taken to assess manure drainage through the slatted floors and ammonia concentrations were measured in the rooms as an air quality indicator. Based on the observations of sow activities, the floor in each room was virtually divided into four areas, namely dunging, high traffic, low traffic and sleeping areas. Floor and animal cleanliness were assessed weekly in the four areas through image analysis. The surface roughness and dynamic coefficient of friction (DCOF) of the two concrete floors were measured in the four areas. The results showed there was no significant difference in air quality, floor and animal cleanliness between the two tested floor configurations. The friction tests revealed that the length of time of floor usage by sows had a significant effect on the roughness and DCOF of concrete floors, with a sharp reduction in the DCOF after the first week of use because manure stuck in the pores of the concrete surface reduced the interlocking between the asperities of the contact surfaces. No significant differences in the roughness and DCOF were found between the floor areas associated with different animal activities and between the two floor configurations.

A two-dimensional (2D) stick model was developed to simulate sow walking on the concrete floors. The model consisted of thirteen (13) connective body joints to form a simple stick figure that approximated a sow's body skeleton. The video images of sows with reflective markers on the bodies walking along a corridor of concrete floor were analyzed and translated into a 2D coordinate dataset. A step of walking was modelled as three consecutive phases of motion: acceleration for a foot leaving the ground; constant speed for foot swinging; and deceleration for the foot touching the ground. The displacements of each joint at a time step in x- and y-directions were modelled by a combination of first and 2nd order polynomial functions. The coordinates of all joints were linked by synchronizing the motions of each joint at a given time step. The predicted joint coordinates at each time step were then used to calculate a selected set of characteristic gait parameters, including the stride length and stance time for fore- and hind limbs, diagonality, back angle and walking speed. Based on the comparisons of the predicted gait parameters between the lame and non-lame sows, the criteria were established for using the predicted gait parameters to detect sow lameness. The walking speed and forelimb stride length combination was defined as the best model indicator for lameness detection with an accuracy greater than 92%.

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Dedication

This thesis is dedicated to my parents, Ping Yan and Fengying Jia for their unconditional love and support.

Thesis Structure

This thesis is a “sandwich thesis” as per the format outlined by the Faculty of Graduate Studies, University of Manitoba. The thesis begins with a general introduction, objectives and literature review, then three manuscripts each contains an abstract, introduction, materials and methods, results and discussion, and conclusions, and finally a section of overall conclusions and recommendations.

Contributions of Authors

The thesis author, Xiaojie Yan, was the main contributor and first author of all the manuscripts presented in the thesis. Ms. Yan's contributions to the work included designing the studies, carrying out experiments, performing data analysis, developing the simulation model, writing all manuscripts, submitting the manuscripts, and responding to reviewer's comments. Dr. Qiang Zhang contributed to the conception of the study and supervision of the project. Dr. Laurie Connor conceived the original idea of the project, supervised the work and provided resources for in-barn experiments of the study. Dr. Nicolas Devillers provided the video data and gave valuable suggestions and guidance in gait analysis and model development. Dr. Kristopher Dick contributed to the conceptualization of the in-barn study and design of slatted concrete floors. All authors provided critical feedback and helped shape the research, analysis and manuscript.

At the time of writing (May 2021), one of the three individual manuscripts has been published as a peer-reviewed conference proceeding (Chapter 3), one has been published in a peer-reviewed journal (Chapter 4) and one is submitted to a peer-reviewed journal (Chapter 5). The publications are listed below. Part of Chapter 3 is also included in a peer-reviewed publication (Appendix C), which listed Xiaojie Yan as a second author. Ms. Yan's contributions to the publication included writing the sections of floor characteristics, air quality and pen cleanliness in the manuscript, carrying out the corresponding experiments, performing data analysis and responding to some reviewer's comments.

- Yan, X., Zhang, Q., & Connor, L. (2018). Effect of slatted floor configuration on air quality and floor cleanliness in a sow barn. *10th International Livestock Environment Symposium (ILES X)*, Omaha, Nebraska, USA.
- Yan, X., Zhang, Q., Connor, L., Devillers, N., & Dick, K. (2021). In-barn measurements of surface roughness and friction of slatted concrete floors in sow gestation rooms. *Biosystems Engineering, 205*, 137-145.
- Yan, X., Zhang, Q., Connor, L., Devillers, N., & Dick, K. A 2D stick model for simulation of sow walking on concrete floors and detection of sow lameness. Submitted to *Biosystems Engineering*.

- Devillers, N., Yan. X., Dick, K., Zhang, Q., & Connor, L. (2020). Determining an effective slat and gap width of flooring for group sow housing, considering both sow comfort and ease of manure management. Livestock Science, doi.org/10.1016/j.livsci.2020.104275.

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1. Introduction

1.1 Background

Slatted concrete floors are commonly used in sow barns for durability and convenient manure handling. The most significant advantage of slatted floor is that manure drops through gaps between slats into a slurry pit (or gutter) underneath the slatted concrete floor (Ye et al., 2007) to minimize manure accumulation on the floors, and manure is either stored in the pit (deep pit systems) or drained from the gutter and pumped to an outdoor storage facility. Clean floors with less manure accumulation could reduce ammonia emission and provide the best possible environment to animals (Aarnink et al., 1996). However, concerns have been raised about the welfare of sows housed on slatted concrete floors in terms of increased occurance of claw lesions and lameness (Anil et al., 2007; Cador et al., 2014; Gjein & Larssen, 1995a). Therefore, a well-designed slatted concrete floor should not only promote the manure handling but also minimize the impairment of sow feet and leg health as well.

An adequate flooring requires appropriate slat and slot widths (configuration) for easy manure removal and best welfare of sows. The gaps of the slatted floor are critical for good drainage of manure, thereby decreasing ammonia emissions (Svennerstedt, 1999). On the other hand, they may have a negative impact on dewclaw overgrowth and wrenching, heel lesions and sows' gait (Anil et al., 2007). The Canadian Code of Practice (National Farm Animal Care Council, 2014) only asks to ensure that the slat widths maximize the contact area with the soles of pigs' feet and the gap (slot) widths be appropriate for the sizes of pigs. North American swine industries commonly use a slatted concrete floor with 125-mm slat width and 25-mm gap. Scientific knowledge about the most effective slatted floor configuration for sows is still lacking. Aarnink et al. (1997) found no significant difference in the ammonia emission between two concrete slatted floors in fattening piggeries, one with 100-mm slats and 20-mm gaps and the other with 70-mm wide slats and 18-mm wide gaps. Falke et al. (2018) compared two floor configurations, one with a slat width of 153 mm and a gap of 15 mm (5% perforation) and the other with 110-mm wide slats and 15-mm gaps (10% perforation). No effect of floor configuration on claw and leg lesions of fattening pigs were found.

Not only the gaps of slatted concrete floor cause concerns for the claw and leg health of sows, but also the surface properties, such as roughness and coefficient of friction. The floor surface is a key factor for skin and claw lesions since the sow is in physical contact with the floor for all activities, such as walking, standing and lying. Furthermore, the surface properties of concrete floors in barns are affected by manure on the surface, as well as animal activities. The surface properties are directly related to slipperiness and abrasiveness of floors. Slippery floors may cause claw and joint injuries of sows when slipping or falls occur. Many studies have shown that the animals alter their gait to adapt to fouled floor conditions and avoid slipping (Phillips & Morris, 2001; Thorup et al., 2007; von Wachenfelt et al., 2009). Rough floors can increase the risk of claw lesion and bursae due to abrasion (Gjein & Larssen, 1995b; McKee & Dumelow, 1995; KilBride, 2008; Franck et al., 2007). Understanding the frictional interaction between concrete floor surface and sow hoof or skin is essential in optimizing the floor design and thus improving animal welfare (Bonser et al., 2003). The coefficient of friction (COF) is a common parameter to indicate the floor slipperiness (Webb & Nilsson, 1983). Slip occurs when the required COF exceeds the actual COF at the claw-floor interface (van der Tol et al., 2005). Although friction of concerete surfaces has been studied extensively, little is known about how animal activities affect surface properties of concrete floors in pig barns.

Lameness is a major welfare issue in the swine industry (Kirk et al., 2005; Pluym et al., 2011) and one of the major reasons for culling sows with a reported culling rate of 11.0% in North America (Dewey et al.,1992) and 15.2% in US (Schenck et al., 2010). Culling could lead to significant economic losses for producers due to the reproduction loss, additional labour and cost of replacing sows (Grégoire et al., 2013; Pluym et al., 2013b). The possible causes of lameness related to floors include foot lesions, infections (Nalon et al., 2013), inappropriate floor properties, such as low floor friction, gap widths of slatted floors and insufficient floor space allowance (Thorup et al., 2007; Jørgensen, 2003; Li et al., 2018). Detection and evaluation of lameness is critical in improving welfare and productivity of pigs. Most quadrupeds, including pigs, normally have a symmetrical gait, whereas lame ones do not (Griffin et al., 2004; von Wachenfelt et al., 2008). Therefore, lameness is often detected by analyzing the gait. Visual locomotion scoring is a simple method commonly used in commercial farms (Main et al., 2000), but is subjective and of limited reliability (Channon et al., 2009) for detecting subtle lameness. Kinetics and kinematics are common objective ways to investigate abnormal gait of pigs (Von

Wachenfelt et al, 2010). Kinetics studies the forces involved in motion (Hall, 1995), while kinematics measures the geometry of movement without considering the forces that cause the movement (Clayton & Schamhardt, 2001). Kinetics is usually studied by using force plates to measure the asymmetry of weight distribution on legs (Conte et al., 2014; von Wachenfelt et al., 2009). Kinematics is often investegated using video recording to capture the movement of an animal with markers on anatomical landmarks. However, specific studies about gait simulation models of pigs and other farm animals are scarce. There is a need to have a comprehensive understanding of pig walking biomechanics to add insight into the development of gait simulation models and lameness detection.

This thesis research addressed two significant issues of concrete flooring in sow barns: (i) configurations and properties of slatted concrete floors as related to manure drainage and slipperiness, and (ii) gait of sows on slatted concrete floors as related to lameness.

1.2 Objectives

1. To experimentally assess the performance of an optimized configuration of slatted concrete floor with 105-mm slats and 19-mm gaps in terms of manure drainage and indoor air quality.
2. To quantify the surface properties (roughness and friction) of slatted concrete floors in use by gestating sows by determining:
   a) the relationship between the surface properties and time of use;
   b) the relationship between the surface properties and animal activities.
3. To develop a 2D (two dimensional) stick model to simulate sow walking on slatted concrete floors.
4. To investigate the potential of using the stick model to detect sow lameness.

1.3 Thesis contributions

This thesis presents three studies of concrete flooring in sow barns and sow gait as related to animal welfare. The significant findings and contributions of this thesis research are:

1. The narrow slat and gap floors could be used in sow gestation barns to improve animal welfare without negative impact on manure drainage and in-barn air quality.
2. The dynamic coefficient of friction (DCOF) of the newly installed concrete floors decreased sharply in the first two weeks of use by animals. A novel friction model of two serrated surfaces explained that the sharp decrease in DCOF was due to reduction of interlocking between the asperities of the animal foot and the concrete surface when the concrete pores were filled with manure.
3. A two-dimensional stick model was developed to simulate sow walking on concrete floors and detect sow lameness. The 2D stick model composed of 13 joints connected by 12 (rigid) sticks that approximated a sow's body skeleton. A unique feature of the stick model is taking the inter-limb coordination into account. The model showed an adequate ability to detect sow lameness.

2. Literature Review

2.1 The effect of floor configuration on barn environment

Slatted concrete floors are made of concrete slats with gaps between slats to allow manure to drain away. Generally speaking, the wider the gaps, the easier the manure drains. While wider gaps may favor the drainage of manure, they can cause claw injuries (catch toes). Floors with widths of 125 mm slats and 25 mm gaps are commonly used for sows in North America. The Canadian Code of Practice for pigs provides no specific configuration specifications but advises that slat widths should maximize the area of sole contact and gap widths be appropriate for the sizes of pigs (National Farm Animal Care Council, 2014). The European Union requires a minimum slat width of 80 mm and gaps no greater than 20 mm (Council of the European Union, 2008).

2.1.1 Ammonia in barns

Manure gases in livestock buildings can negatively impact the health of animals and workers, and even the air quality, water and soil system in the community. Ammonia (NH_3) is one of the major gaseous pollutants in swine production correlated with animal health concerns, such as eye irritation, pneumonia and pleurisy (Donham, 1991; Gerber et al., 1991; Ni et al., 2000). The typical ammonia concentrations in swine finishing buildings range from 0 to 40 ppm (Heber et al., 2005). Hamelin et al. (2010) tested the ammonia concentrations in 16 sow buildings in Germany and reported that the average ammonia concentration was 13±4 ppm. The commonly recommended threshold for ammonia in pig barns is 20 ppm (Commission Internationale de Genie Rural, 1984). The Canadian Code of Practice requires ammonia concentration at pig level less than 25 ppm in swine barns (National Farm Animal Care Council, 2014).

In sow barns, ammonia mainly comes from the surfaces of wet manured floors and slurry pits under the slatted floors (Aarnink et al., 1997). Ammonia is generated from the decomposition of urine and feces (Bussink & Oenema, 1998; Svennerstedt, 1999). Therefore, the slatted floor can help reduce the emitting surface area by achieving manure drainage as much as possible to bring down the ammonia emission (Aarnink et al., 1997; Philippe et al., 2011; Ye et al., 2007). Different slatted floor configurations may result in different degrees of manure accumulation on floor surfaces, thus different ammonia emission rates. Generally speaking, larger gaps would result in better manure drainage, and thus lower ammonia emission. However, larger gaps would have higher potential of causing foot problems.

Several studies have been carried out to evaluate the ammonia emission and concentration in pig houses equipped with slatted concrete floors. Philippe et al. (2016) evaluated the ammonia and greenhouse gas emissions on two partially slatted concrete floors (15% and 2.5% drainage openings) in pens for group-housed gestating sows. They found the ammonia emission for the floor with 15% openings was significantly lower. Aarnink et al. (1997) found no significant difference between two concrete slatted floors, one with 100-mm wide slats and 20-mm gaps and the other with 70 mm slats and 18 mm gaps, in terms of ammonia concentration in the buildings for fattening pigs. Hoeksma et al. (1992) estimated that floor emissions accounted for 30% of total ammonia emissions in pens with 62% of the floor area slatted. Aarnink et al. (1996) had similar results that floor emission was 40% of the total ammonia emission in pens with 25% of the floor area slatted and 23% in pens with 50% of the floor area slatted.

It is clear that ammonia emission from floors is positively correlated to the amount of floor surface where manure accumulates. Also, manure accumulation on a floor surface is affected by the floor configuration: less manure accumulation on slatted floors than solid floors; and less manure accumulation on slatted floors with higher percentage of gaps and wider gaps.

2.1.2 Manure drainage and floor cleanliness

In a typical slatted floor, part of the manure can drop through the gaps, while some manure still remains on the slats. Effective drainage of manure on slatted floor is a key in minimizing pen soiling. Ni et al. (1999) determined the floor contamination by estimating the proportion of the partly slatted floor surface covered by wet manure. They found the ammonia emission rate had a high correlation coefficient (r=0.852) with floor contamination.

Researchers developed several quantitative ways to evaluate the manure drainage and surface cleanliness of the slatted concrete floors. Næss et al. (2014) evaluated the alley cleanliness in dairy cubicle barns by measuring the manure accumulation (depth of manure). The results showed that the manure accumulation of slatted floors was significantly less than solid floors. Using a weighing method, but under laboratory conditions, Ye et al. (2007) compared two concrete slatted floors with the same slat width (100 mm) and different gap width (10 mm and 5 mm) to estimate the manure-separation performance of the floors. They reported that the floor with 100-mm slats and 5-mm gaps showed lower feces drainage and good urine drainage. Aarnink et al. (1997) used a non-quantitative method to assess manure drainage. They drew the shape of the fouled area on the slatted floor map based on visual observation, then a rectangle was drawn around the fouled area and the fouled part within the rectangle (excluding the gaps in the slatted floor) was estimated.

Floor cleanliness certainly affects animal cleanliness because pigs spend most of the time lying (resting and sleeping) on the floor (Huynh et al., 2005). Pig cleanliness is an important indicator of animal welfare and it is also necessary to ensure the cleanliness of animals going to slaughter according to Safe Food for Canadian Regulations (2018). Minvielle and Le Roux (2009) assessed the cleanliness of pigs housed on different floor types using a five-point visual scoring method on four body areas: rear, back and both flanks. They found that pigs on slatted floor were cleaner than on partly slatted floors and outdoors.

2.1.3 Effect of environmental conditions on ammonia and manure drainage

For the specific purpose in this study, i.e., investigating the effect of floor configuration on ammonia and manure drainage, the indoor environmental conditions should be kept as similar as possible since researchers (Hoeksma et al., 1992; Svennerstedt, 1999) discovered that temperature and relative humidity can influence the NH_3 level and the cleanliness of floor and animals in pig barns. Voermans and Hendriks (1995) reported that the finishing pigs befouled the pens in summer more than in winter. Ni et al. (1999) found the indoor temperature and ventilation rate had strong influences on the NH_3 emission rate when the floor contamination was high in fattening pig houses. In pig barns with mechanical ventilation systems, the ventilation rate varies seasonally to maintain the appropriate indoor temperature and humidity. This could affect the ammonia level in the barn, which should be considered during any in-barn environment evaluation.

The indoor climate has an impact on animal behavior, which can result in a change of floor hygiene. For example, temperatures affect sows lying behaviors and postures, such as lying more on slatted floors in summer than in winter (Aarnink et al., 1997), which could increase the fouling of floor (Aarnink et al., 2001). The temperature of the surface of slatted floor is generally 3 to 5 °C cooler than an insulated solid floor (Randall et al., 1983). Huynh et al. (2004) observed that pigs changed the preferred lying location from the solid floor to the slatted floor as temperature increased, and the pigs only lay on the solid floor when ambient temperature was under 18.8 °C. At high temperatures, pigs tend to look for a cold floor to lay on, such as the dunging area, to increase heat loss (Ducreux et al., 2002). Lying in the dunging area can help the pig cool down, however, also makes the pig hygiene worse. High humidity can accentuate the effect of temperature on the pig's behavior (Huynh et al., 2005).

2.2 Surface properties of floors

2.2.1 The effect of floor characteristics on foot and leg health of pigs

Lameness of sows is a major concern to the swine industry. According to a study reported by Seddon and Brown (2013), the prevalance of lameness in sows ranged from 8% to 46% in Canada. Heinonen et al. (2006) and Kilbride et al. (2009a) evaluated the lameness in sows to be between 8.8 % and 16.9%.

Inappropriate floor properties are considered as a major reason for lameness and claw injuries (Gjein, 1994; Ehlorsson et al., 2002; Olsson & Svendsen, 2002; Lahrmann et al., 2003). Although many studies (Anil et al., 2007; Conte et al., 2014; Gjein & Larssen, 1995a; Grégoire et al., 2013; Nalon et al., 2013) have been carried out to assess the claw lesions and lameness in sows, only a few were focused on the effect of floor characteristics on the foot lesion and leg problems of pigs (Applegate et al., 1988; Devillers et al., 2019; Starvrakakis et al., 2014a; Thorup et al., 2007; von Wachenfelt et al., 2008). Gjein and Larssen (1995c) studied the impact of different floor types on claw health for sows. They found that loose-housed herds with straw bedding had fewer claw lesions than stalled or tethered sows and interestingly, there were no significant differences between plastic slats and concrete slats in terms of major claw lesions. Falke et al. (2018) found the claw and leg lesions of pigs kept on rubber mats were fewer than pigs on concrete. Rubber flooring improved pig gait adaptation due to more effective transmission of forces from the legs to the elastomer material (von Wachenfeldt et al., 2010).

The Canadian Code of Practice for pigs (National Farm Animal Care Council, 2014) recommended rubber mats for the pigs showing signs of lameness.

Applegate et al. (1988) evaluated young pigs' gait on different concrete floor surfaces finished with fine and coarse sand, fine and coarse broom, wood float and steel trowel. Their results showed that the skid resistance of different concrete surfaces did not influence the stride length, velocity and stance time significantly. However, on a more slippery concrete surface (fouled), pigs adapted their gait by reducing walking speed, stride length and diagonality (von Wachenfelt et al., 2008). Thorup et al. (2007) also discovered that pigs adapted their gait by walking slowly according to the floor condition to avoid slipping on contaminated and potentially slippery floors compared with dry floors. On the other hand, if the floor is slightly slippery, the sows have to make special exertions which may lead to abrasions (Franck et al., 2007). For example, pigs tend to change the contact angle between the foot and the ground and the walking speed on different floor materials. The forces applied on the floor by pig foot during walking are counteracted by the forces exerted in conflicting directions in foot tissue (Hanson et al., 1999; von Wachenfelt et al., 2009). Therefore, different friction properties of floor materials could cause abrasions to different extents. Rough floor surface may increase the risk of claw and limb lesion (Gjein & Larssen, 1995b; McKee & Dumelow, 1995; KilBride, 2008), but wet and fouled floor surface may make the hooves more vulnerable by softening the skin (Zurbrigg, 2006) and increase the risk of infection (Gjein & Larssen, 1995a).

Slatted concrete floors can have a negative impact on dewclaw overgrowth and wrenching, heel lesions and sows' gait (Anil et al., 2007). To minimize the problems associated with slatted floors, the gap width of slatted floors should be appropraite for the size of pigs (National Farm Animal Care Council, 2014). Webb (1984) developed an equation to determine the maximum safe void percentage of floor based on a pig's weight. For sows, a maximum void percentage of 20% was suggested for concrete slatted floors. Falke et al. (2018) compared two floor configurations, one with a slat width of 153 mm and a gap width of 15 mm (5% perforation) and the other with 110-mm wide slats and 15-mm wide gaps (10% perforation), and found no effect of floor configuration on claw and leg lesions of fattening pigs. Stavrakakis et al. (2014a) studied the gait of pigs housed on fully slatted and partly slatted concrete floors for about 11 weeks and found that the floor type had no significant effect on pigs' gait. However, Devillers et al. (2019)

measured sows' gait on slatted concrete floors with different combinations of slat (85, 105 or 125 mm) and gap (19, 22 or 25 mm) widths. It was revealed that the gap width had a significant effect on some gait parameters such as back angle, stride length, foot height, and carpal and tarsal joint angle amplitudes, and the slat width significantly affected foot height, and carpal and tarsal joint angle amplitudes.

2.2.2 Measurements of roughness and friction of concrete floors

Friction is an important indicator of the floor conditions, affecting the interaction between animal claw and floor surface, often referred to as slipperiness (Webb & Nilsson, 1983). The coefficient of friction (COF), defined as the ratio between frictional force (horizontal) and normal force (vertical), is commonly used as a measure of floor slipperiness. When an object is resting on a contacting surface, the frictional force required to initiate the movement of the object is measured to calculate the static COF (SCOF). The frictional force required to maintain the movement of the object at a constant speed is measured to determine the dynamic COF (DCOF). Both SCOF and DCOF are determined from measured forces by the following equation (Chang et al., 2001).

$$\text{COF} = \frac{F_k}{F_n} \qquad (2.1)$$

where, F_k = frictional force, N;

F_n = normal force, N.

The DCOF is usually lower than the SCOF (Hall, 1995). Generally speaking, the COF is related to roughness of a floor surface (Chang et al., 2001), i.e., the smoother surfaces, the lower COF, and the more slippery the surfaces. The COF can be influenced by the presence of fluid on the floor surface (Redfern & Bidanda, 1994), and the measured value may even vary with the test equipment and methods (Webb & Nilsson, 1983). Slip occurs when the COF is too low at the claw–floor interface (van der Tol et al., 2005). Insufficient friction between the foot and the floor may also affect the pig's gait (Li et al., 2004; von Wachenfelt et al., 2008). According to Webb and Nilsson (1983), a sufficient COF value for animals standing or in locomotion is at least 0.35-0.40.

Roughness is a component of surface texture and profile. The commonly used roughness parameters in tribology are the arithmetic average height (R_a), root mean square (R_q), skewness (R_{sk}), and kurtosis (R_{ku}). The R_a is usually used in practice and defined as the arithmetical mean of the absolute values of the profile deviations from the average line of the roughness profile (ISO 4287, 1997). However, R_a is not sensitive to the fine changes of asperity peaks and depths of valleys (Kovalev et al., 2019).

Several studies have been reported on measuring the COF and roughness of the concrete surfaces with simulated in-barn floor situations. Nilsson (1988) described a drag method to test the DCOF between "hoof" simulated by a block of polyethylene and floor surfaces. The polyethylene was selected to simulate the animal hoof due to its durability and similar COF as a dry hoof. Franck et al. (2007) used the same method to assess DCOF of both dry and wet concrete floors, but using real bovine claws (from slaughter cows). In testing the wet concrete floor, they used bovine claws immersed in water overnight on the floor with a layer of water. They found that the DCOF in wet conditions were larger than that in dry conditions. They also evaluated the roughness of the concrete floors by measuring the height of the surface peaks and valleys with a high-precision laser beam. The DCOF and the average roughness had positive but low correlations. However, Bonser et al. (2003) found the DCOF between concrete floor and bovine claw differed significantly between different roughness treatments. But they did not quantify the roughness of the floors and only categorized the floor samples as "smooth abrasive" and "rough abrasive". Franck and De Belie (2006) tested five concrete floors with different surface structures obtained by using different finishing methods: metal float, wooden float, brushed, mildly and heavily sandblasted. They showed that the roughest surface was the concrete heavily sandblasted with R_a of 0.488 mm and the smoothest was the one finished with a metal float with R_a of 0.062 mm.

Researchers (Thorup et al., 2007; Powers et al., 2002; van der Tol et al., 2005; von Wachenfelt et al., 2009) also tested the frictional force directly from a walking animal by using a force plate. Slips usually occur when the animals fail to adapt to the floor conditions and the required, or utilized COF (UCOF) exceeds the COF of the claw-floor interface (von Wachenfelt et al., 2009). The UCOF can be determined from force plate recordings of the ground reaction forces (GRF), i.e., as the ratio between the horizontal and normal GRFs at the claw-floor interface (Redfern, et al., 2001). van der Tol et al. (2005) measured GRF of dairy cows walking on a non-slippery rubber-covered concrete floor and observed that the UCOF was lower than COF during walking, but higher than the maximum COF that concrete floors could provide during stopping and starting of a walk which meant that the incident(s) of slipping might occur. Thorup et al. (2007) measured GRF of pigs walking on dry solid concrete floors and found that the UCOF was the highest at the beginning and towards the end of the stance phase, which was similar to what was reported by van der Tol et al. (2005). They also discovered that pigs adapted their gait to avoid slipping by reducing their walking speed and the peak UCOF on greasy and wet floors compared to dry floors.

The floor conditions in animal barns are subjected to not only the lubricative effect of manure, but also the corrosive effect of manure and mechanical abrasion. De Belie et al. (1997a) found that the slatted floors in pig barns showed degradation within five years in 40% of the farms surveyed. Furthermore, these effects are affected by pig traffic and manure distribution, which are not uniform throughout the barn because pigs often "compete" for space in relatively small areas, where the floors are wet and fouled, and might degrade at higher rates (De Belie, 1997b). Few studies have investigated the in-situ surface properties of slatted concrete floors in pig barns over time.

2.3 Lameness and gait analysis of pigs

Several methods and techniques of gait analysis have been used to detect animal lameness. Locomotion visual scoring is a common method to assess the pig gait by scoring them on a scale from normal to severe lameness (Conte et al., 2014; Main et al., 2000). Conte et al. (2014) used a three-point scale to evaluate lameness of gestating sows: 0 -normal gait, even strides; 1 -abnormal gait, stiffness, but lameness not easily identified; and 2 -lameness detected, shortened strides, sow puts less weight or avoids putting weight on one leg. However, the drawback of this scoring method was its subjectivity and difficulty identifying mild lameness (Pluym et al., 2011; Pluym et al., 2013a). Besides, the locomotion assessment by human is usually prone to lack of the intra and inter-observer reliability (Calabotta & Kornegay, 1982), which is a major issue in quality of gait asessment.

There are some objective techniques for gait analysis, such as kinetics and kinematics. Kinetics is the study of forces involved in motion (Hall, 1995). The force plate is a commonly used device for studying kinetics by measuring the asymmetry of weight distribution among legs. Pluym et al. (2013b) developed a detection system (SowSIS) by using a force plate to measure force stance variables. The preliminary results showed that all lame sows avoided putting weight on the lame leg and shifted weight to the contralateral sound leg. Instead of standing status, Thorup et al. (2007) measured the ground reaction force (GRF) during pig's walking on a force plate and they observed that the centre of gravity was relatively closer to the forelimbs of pigs, with 54% of the body weight carried by the forelimbs. This meant that the forelimbs had a higher probability of suffering leg problems because they carried greater weight than the hindlimbs. They also observed that pigs adjusted braking force and propulsion on wet and greasy floors to avoid slipping. De Carvalho et al. (2009) tested the pressure distribution of pig claws by using a piezoelectric sensing device and reported that the rear legs of pigs applied much more force on the outer claw compared to the inner claw, which explained the reported pathologies found in the literature on hoof-wall cracks and sole ulcers.

Kinematics is another common method to study gait, but focuses on the motion of the points without considering the forces that cause them to move. Video-based analysis system is a popular technique to study kinematics by digitizing the markers on the animal's skin at specific anatomical landmarks in two or three-dimensions. The collected data can provide information on the linear and angular displacements, velocity and accelerations of each marker (Barrey, 1999; Clayton and Schamhardt, 2001). Mohling et al. (2014) used a kinematics tool (GAITFour gait analysis walkway system) to discriminate between sound and lame sows. The lame sows showed increased stride time, decreased stride length, increased stance time and decreased maximum pressure on the lame hoof compared with the sound ones. Stavrakakis et al. (2014b) collected 3D coordinate data of reflective skin markers attached to leg anatomical landmarks while clinically sound and unsound pigs walked on a solid concrete walkway. They showed that unsound pigs altered their gait in terms of joint flexion changes and asymmetry. Grégoire et al. (2013) did gait analysis on three groups of sows (lame, midly lame and non-lame) using kinematics and observed that the lame sows had a lower walking speed than non-lame ones, a shorter stride length than mildly lame ones, and a longer stance time than non-lame and mildly lame sows. Devillers et al. (2019) used kinematics to characterize the gait of sound and lame sows walking on concrete slatted floors with nine combinations of slat (85, 105 or 125 mm) and gap (19, 22 or 25 mm) widths. Nine reflective markers were attached to the standardized spots of each sow's body (Fig. 2.1). They revealed that slat widths of 105-125 mm with gap widths of 19-22 mm had the least effect on the gait characteristics of the sows.

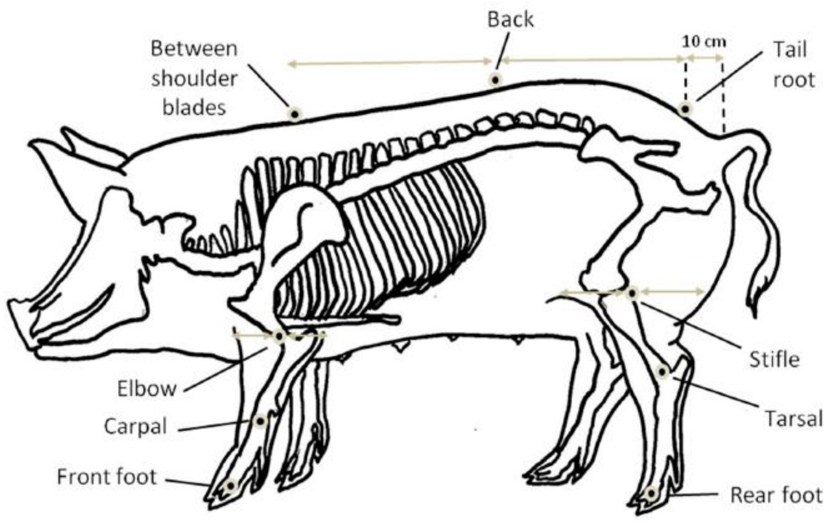


Figure 2. 1. Position of reflective markers on the sow's body (Devillers et al., 2019)

Accelerometers have been used to measure pig behaviour for lameness detection as well (Ringgenberg et al., 2010). Jørgensen (2000) discovered that the stepping behaviour of hind limb(s) during sow standing indicated weight shifting of the hind limb(s) and thus, claw disorders. Conte et al. (2014) used accelerometers to count hind limb stepping behaviour of sows during feeding time, and found an increase of stepping behaviour with lameness. Grégoire et al. (2013) compared five methods of studying lameness of sows, with gait scoring as the reference: footprint analysis, kinematics, accelerometers, lying-to-standing transition, and foot lesion observation. The accelerometer measurements showed that the lame sows spent less time standing, lay down earlier after feeding and tended to step more often during feeding than the non-lame sows. They proved that kinematics and accelerometers could successfully identify lameness in sows.

The gait analysis for the purpose of lameness detection is usually built on the principle of gait symmetry. The past literature (De Carvalho et al., 2009; Grégoire et al., 2013; Stavrakakis et al., 2014b; Devillers et al., 2019) suggested the uneven weight distribution (weight shifting), asymmetrical gait parameters, such as shorter stride length, lower walking speed and longer stance time, and arched back could be used as the best indicators of lameness.

2.4 Gait simulation and characterization

2.4.1 Computer vision technique in animal behaviour analysis

Automatic animal behaviour analysis combined with computer vision is becoming a trend in precision farming. Various studies have been conducted to develop models or automatic systems for behaviour characterization and lameness detection, mostly for dairy cows. Porto et al. (2013) developed a computer vision-based system to automatically detect the lying behaviour of dairy cows in free-stall barns. They used Viola-Johns algorithm (Viola & Johns, 2001; Viola & Johns, 2004) to analyze top-view images from a multi-camera video-recording system. One of the challenges in automatic image processing is image segmentation and feature extraction. Usually the images of barn environment have too much noise to extract the animals from the background. Several studies have proposed algorithms to track animals in the group-housed barn (Hu & Xin, 2000; Shao & Xin, 2008; Porto et al., 2013). However, these studies all have some limitations: (1) the top-view images cannot provide information of leg movements; (2) the animal images must be highly contrasted from the background for image segmentation, which is difficult to achieve in real barns; (3) images are often too complicated for high stocking density.

Lameness detection requires the identification of abnormal gait. Researchers used the arched-back feature of lame animals to develop automatic lameness detection systems. Poursaberi et al. (2010) proposed an algorithm to identify an individual cow walking along a corridor from side view images and score the lameness by calculating the curvature value of a circle fitted through selected points on the back of each cow. The 2D camera systems are used in most studies, however, they have high requirements in camera orientation, lighting and image background (Clayton & Schamhardt, 2001). The 3D camera systems with depth information are attracting researchers' attention. Viazzi et al. (2014) used a 3D camera system to extract the back posture of individual walking cows from top view images. The back spine of the cow was reconstructed by fitting a 4th order polynomial function, and then two ellipses were fitted to the left and right side of the highest point of the curvature (back spine). A set of geometrical parameters related to the cow back posture were then calculated for lameness classification. The 3D method achieved an accuracy of 90% in lameness detection. Van Hertem et al. (2014) improved the algorithm developed by Viazzi et al. (2014) by optimizing the classification performance to eliminate false positives like trips and slips. The cow gait during four consecutive milking sessions were analyzed by the automatic lameness detection system and by a live visual scoring expert as well. The dataset of 186 cows with four automatic lameness score and four live locomotion scores was used to test three different classification methods, i.e., ordinal multinomial logistic regression model, nominal multinomial logistic regression model and linear regression model. The ordinal multinomial logistic regression model showed the best classification accuracy up to 90.9%.

The automatic lameness detection is easier to perform for dairy cows due to milking sessions than for pigs. The videos can be taken when the cows pass a narrow corridor individually and freely walking from the milking parlour to the cowsheds. Zhu and Zhang (2010) developed an automatic algorithm for identification of abnormal gait of pigs based on video analysis. The analysis consisted of three steps: (1) extraction of the moving pig images; (2) modelling of the forelimbs and measurements of the joint angles; (3) gait analysis and classification of abnormal gait. The algorithm achieved an average classification accuracy of 90%. Kongsro (2013) proposed a novel technique to measure pig locomotion by herding the pigs individually from one pen to another. A web camera was mounted in the pen ceiling to obtain pig images in the top view. The binary images of each pig during walking were processed and organized as a stack of binary images to generate a map image of the pig’s movement. The map images were then analyzed by using multivariate image analysis, including the principal component analysis (PCA) to obtain components related to particular movement patterns in pig locomotion. These components could be used to classify or score animals according to this pattern, which might be an indicator of lameness. However, this method was not validated for its reliability and accuracy.

2.4.2 Gait simulation in human and animal studies

Most studies of lameness detection for pigs only examined the abnormalities of gait without looking at inter-limb coordination. Stick (segmental) models have been used to study the inter-limb coordination of animals and humans. The biomechanics of human walking is well understood, and human gait simulations have been reported by many researchers (Zajac et al., 2003a & 2003b). Chan et al. (2016) presented a general sequence of human motion estimation

(Fig. 2.2), based on literature review, which may be applied to animal motion as well. Human motion estimation usually begins with video motion capture to obtain information related to human gait. Different models could be used to simplify capture motion matching, such as sticks, cylindrical and ellipsoids to represent the human skeleton (Mikić et al., 2003). Studies about motion estimation have been silhouette-based (Shen et al., 2009), image-based (Tong et al., 2007) and biomechanical-based (Perales & Torres, 1994). Silhouette-based motion estimation studies the image silhouette of human motion; image-based estimation involves direct analysis of the image motion data; and biomechanical-based approaches focus on the analysis of joint locations, soft tissue and bone in the human body (Moeslund et al., 2006).

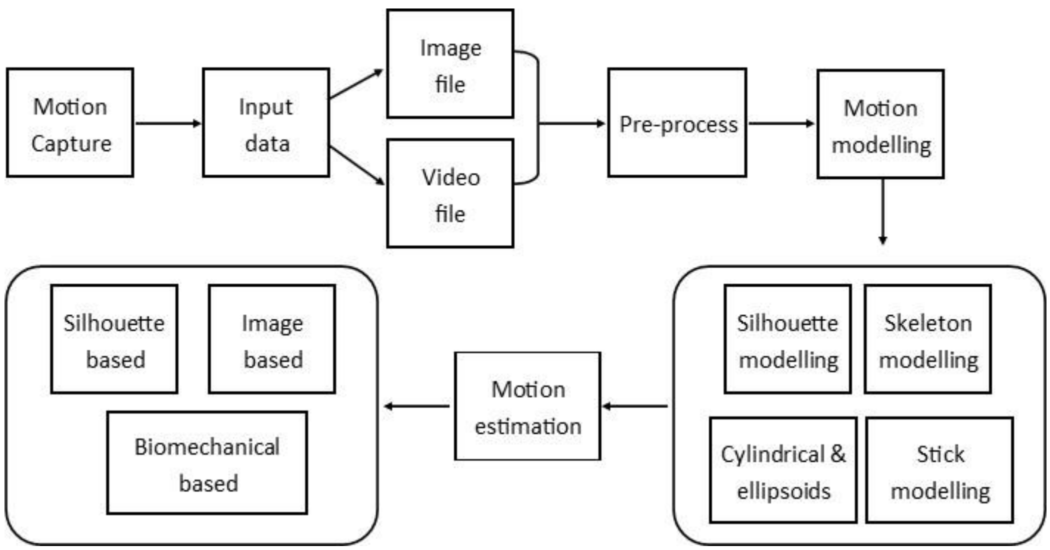


Figure 2. 2. General sequence of motion estimation (Chan et al., 2016)

Stick models have been successfully used to represent the human skeleton for gait or motion estimation (Mikić et al., 2003). The stick figure consisting of joints connected by line segments is the simplest representation of a human body (Aggarwal & Cai, 1999), which was originally proposed by Johansson (1975). The joints of the human body are usally marked by moving light displays (MLD) to study the motion of each joint. The extracted data of joints' motion could then be used for the motion estimation and recognition of the whole stick figure (Wang & Singh, 2003; Aggarwal et al., 1998). Bharatkumar et al. (1994) used the kinematics data of joints of human limbs obtained from video analysis to develop a stick model of the movement of the lower limbs of a walking person. Their model predictions were in good agreement with the real images of human walking. Chan et al. (2016) developed a 2D stick model to resemble a three-segment body structure system to model simple human motions. Their motion estimation model applied the concept of polynomial fitting to the coordinate data. Based on comparisons to the actual motion phases, they confirmed the feasibility of using a 2D stick-model for human motion classification analysis. Ren et al. (2007) developed a seven-segment stick model to simulate human walking using a combined inverse dynamics and optimization method. All segmental motions and ground reactions were predicted from only three simple gait descriptors (inputs): walking velocity, cycle period, and double stance duration. Gritai et al. (2008) proposed a 2D stick model to track motions of human body parts. A human body was modeled as a stick figure with thirteen landmarks, and an action was modelled as a sequence of motions of these stick figures. The algorithm was based on the geometric formulation of human actions and geometric constraints for body joints estimation. Researchers also used simplified sticks representing human legs to model passive dynamic walking in a pure-mechanics perspective (McGeer, 1990; Moghadam et al., 2018). Garcia et al. (1998) presented a simple 2D, two-link model, vaguely resembling human legs which could walk down a shallow slope, powered only by gravity. This model showed stable walking modes and allowed the use of analytic methods to study some basic dynamics of human walking.

Some researchers have adopted stick models for human studies for quadrupeds' gait simulations. Fischer and Blickhan (2006) reviewed the kinematics of the tri-segmented therian limb from mouse to elephant in order to explore general principles of the therian limb configuration and locomotion. They also explored how the tri-segmented leg affected the design of the musculoskeletal system and the operation of legs during locomotion. Catavitello et al. (2015) used a stick model to represent the segments and markers of dogs to study the kinematic coordination of different gait (walk, trot, gallop, and swim). The inter-segmental coordination patterns of the dogs were studied and compared during the four forms of quadrupedal locomotion. Polet and Bertram (2019) presented a simple quadrupedal model to investigate four-beat walking, two-beat running, and pseudo-elastic actuation as energetically optimum. Their inelastic, planar model consisted of two point masses connected with a rigid trunk on massless legs. Using input parameters based on measurements for dogs, their model predicted the correct phase offset in walking and a realistic walk-trot transition speed. The model could also spontaneously predict the double-hump ground reaction force in walking, and the smooth single-hump profile in trotting.

Generally, the stick model is based on the observations of kinematic movements of supporting bones or joints of humans or quadrupeds. The simulated results of stick models can be later used for studying the movement patterns, predicting the joint motions, and estimating the gait parameters. However, few stick models have been used for simulating pig movements.

3. Effect of Slatted Floor Configuration on Air Quality and Floor Cleanliness in a Sow Barn

3.1 Abstract

This study was carried out to investigate the effect of slat and slot widths of slatted concrete floor on air quality and floor cleanliness in sow gestation rooms. Two different configurations of concrete slatted floor were tested in two gestation rooms: room #1 with 105 mm wide slats and 19 mm slots, which was shown to be the best configuration for animals based on a kinematics study; and room #2 with 125 mm wide slats and 25 mm slots, which is the most common configuration currently used in sow barns. Temperature and relative humidity were recorded continuously in each room. Ammonia concentrations were measured in each room as an air quality indicator. Time-lapse cameras in each room took pictures of the floor hourly every week for the assessment of the cleanliness of the floors and the sows. The results showed that there was no significant difference in air quality, cleanliness of floor and cleanliness of sows between the two slat-slot configurations.

Keywords: Ammonia, Gestation sows, Manure, Slatted floor.

3.2 Introduction

The slatted concrete floors are widely used in pig barns to achieve easy manure removal to enhance the indoor environment, as well as to reduce the labor cost. Pig manure is the major source of ammonia emissions in pig barns and ammonia is an important environmental pollutant which is harmful to human and pig health (Ni et al., 2000). Less manure accumulation on the floors, lower emissions of ammonia in barns (Svennerstedt, 1999). Ammonia concentration is a key indicator of the indoor air quality. High concentrations of ammonia can irritate the skin and harm the eyes of animals and humans (Gerber et al., 1991) and as well as the respiratory tract (Urbain et al., 1994).

Emissions of ammonia from livestock originate largely from urea excreted with urine and wet manure (Bussink & Oenema, 1998). Therefore, the slatted floor should be designed in such a way that as much as possible of urine deposited on the floor will run off quickly to the manure collection system to minimize ammonia emission (Aarnink et al., 1997). Ni et al. (1999) found that the ammonia emission rate had a high correlation coefficient (r=0.852) with floor contamination of manure. Hoeksma et al. (1992) estimated that floor emissions accounted for 30% of total ammonia emissions in pens with 62% of the floor area slatted. Aarnink et al. (1996) estimated floor emission was 40% of the total ammonia emission in pens with 25% of the floor area slatted and 23% in pens with 50% of the floor area slatted. Minvielle and Le Roux (2009) used a five-point visual scoring method to assess the cleanliness of pigs housed on different floor types during fattening, and observed that the pigs housed on slatted floor were cleaner on partly slatted floor.

Although the gaps of slatted floor may reduce manure accumulation on the floors, inappropriate slat-slot configurations of slatted floor are usually considered as the main reasons for lameness and claw injuries of pigs (Ehlorsson et al., 2002; Olsson & Svendsen, 2002; KilBride et al., 2009b). Gjein (1994) studied the influences of different floor conditions on claw health for sows and found that inappropriate design of slatted floor can lead to wounds and formation of cracks on claws of sows. Therefore, appropriate configurations of slat width and gap width for slatted floor are supposed to not only achieve effective drainage of manure but also minimize the impairment of pig gait. Based on a kinematics study (the first phase of this on-going project), sow gait characteristics on different slatted floors were investigated. Nine combinations of three slat widths (85, 105 and 125 mm) and three gap widths (19, 22 and 25 mm) were tested. The results showed that slat width of 105 mm and gap width of 19 mm were the best configuration (Devillers et al., 2019). As a follow up, the current study aimed to assess the indoor ammonia level and manure drainage (cleanliness of floor and animals) for the configuration of 105 mm slat and 19 mm gap, and compare it with the commonly used 125 mm slat and 25 mm slot configuration. The specific objectives of this study were to: (1) quantify the manure accumulation on the floors and cleanliness of pigs; and (2) determine and compare ammonia levels in the rooms with two different floor configurations.

3.3 Material and methods

3.3.1 Gestation rooms and herd management

The experiment in this study was carried out in the swine unit of the Glenlea Research Station, University of Manitoba. Two newly manufactured slatted concrete floors with two different configurations (Barkman Concrete Ltd., Steinbach, MB, Canada) were installed in two rooms identical in dimensions. Each room had two pens of 8.6 m in length and 6.0 m in width, and the test floors were installed in one pen in each room, that is, only 50% of the room was used in the experiment (Figure 3.1). One pen in room #1 (right room in Figure 3.1) was equipped with fully slatted flooring of 105 mm slats and 19 mm gaps and one pen in room #2 (left room in Figure 3.1) had fully slatted flooring with configuration of 125 mm slats and 25 mm gaps. The slatted floors in room #1 and room # 2 consisted of 96 and 80 concrete panels, respectively. Each concrete panel was 107.0 cm long × 50.0 cm/ 60.0 cm wide × 7.6 cm deep (Figure 3.2). The experiment was conducted for two gestations cycles: one from June 27th, 2016 to October 2nd, 2016 and the other from November 2th, 2016 to February 27th, 2017. For both cycles, the tests in room #1 started (gestating sows entered into the room) 3 weeks earlier than room #2, as dictated by the normal barn flow. Between the two cycles, the slatted floors of both rooms were cleaned by high pressure washing. There were 24 pregnant sows housed in each pen (room), allowing 2.2 m^2/animal, from 5 weeks to 15 weeks of gestation. Sow groups were balanced for age and size across flooring treatments. The sows in both rooms were managed the same way as in typical commercial gestation operations. Each pen was equipped with an electronic sow feeder (NEDAP, New Standard Ag Inc., Saint Andrews, MB), and three automatic waterers. The ESF allowed sows to be fed individually 2.3 to 2.7 kg/day of a commercial gestation diet (12.28 MJ /kg ME, 13.5 % CP) according to the body condition and stage of pregnancy. The desirable indoor temperature of the two rooms was maintained by a controller (EVS-22HA, GSI Electronics Inc., St-Hubert, QC), which controlled room heating and ventilation. Three-stage ventilation was achieved by two roof-mounted (chimney type) exhaust fans and two rows of box-type air inlets in each room (Figure 3.3). It should be mentioned that heating and ventilation in the rooms were controlled solely by the set temperature, and therefore, on-off of heaters and fan speed (ventilation rate) varied with the outdoor temperature as in commercial barns and variable ventilation rates were not measured. Lights were set on timers to come on at 07:00 h and off at 19:00 h during the entire test period.

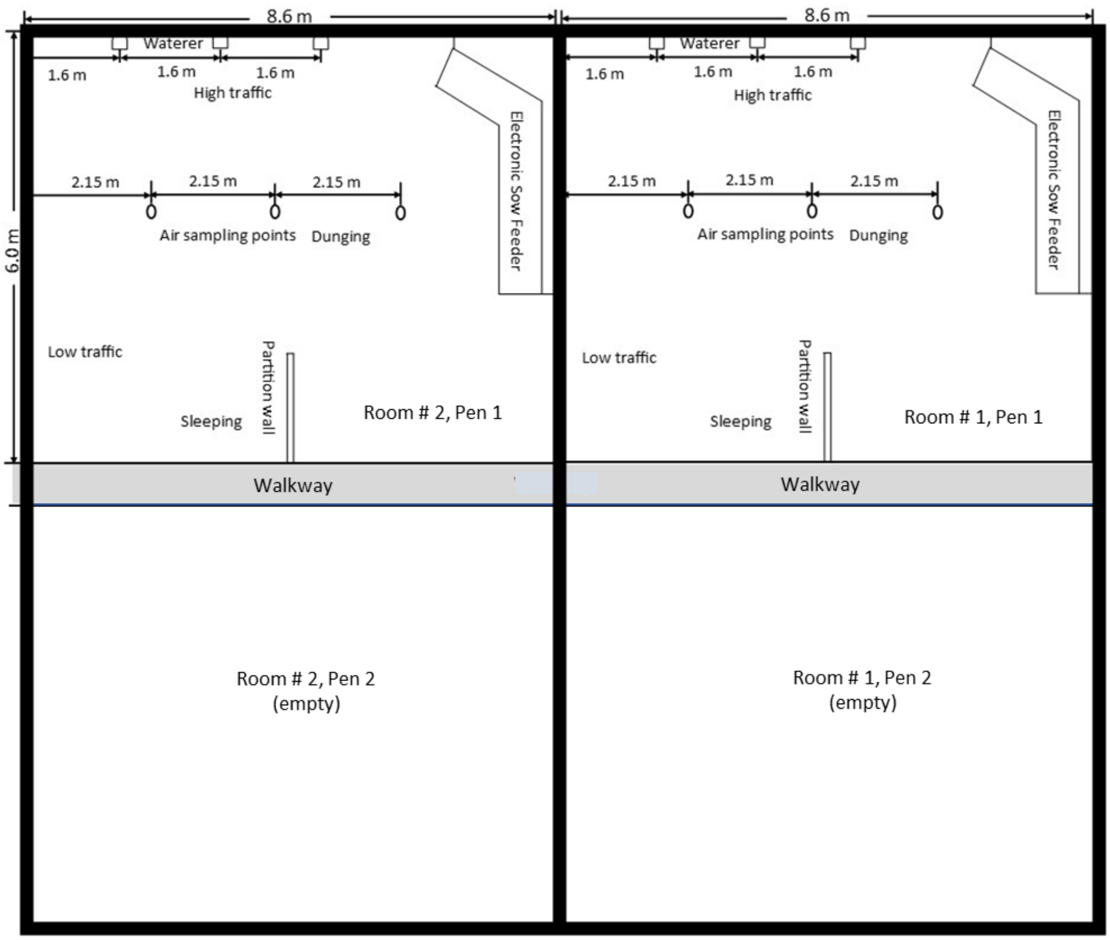


Figure 3. 1. The layout of two gestation rooms where the experiment was conducted

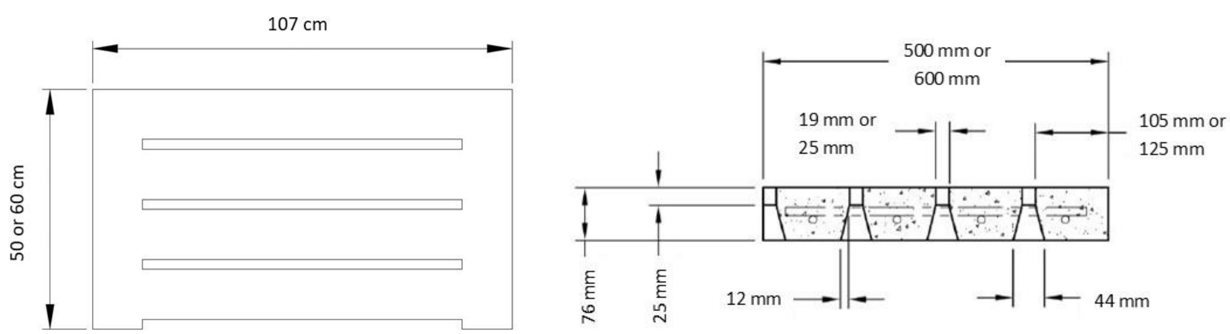


Figure 3.2. Detailed drawing of concrete panels of the slatted concrete floors in gestation rooms (plan view and side view)

Figure 3. 3. The layout of ventilation fans and air inlets

3.3.2 Assessing indoor air quality

3.3.2.1 Ammonia concentration

A Thermo NH_3 17C Analyzer (Thermo Fisher Scientific, Waltham, Massachusetts, USA) was used to measure the ammonia concentration by continuously sampling air at three sampling points for each room. As shown in Figure 3.1, one sampling point was set up in the feeding area, one in the middle of the pen, and one at the other side of pen opposite to the ESF. Air was drawn by a pump through sampling tubes (manifold) mounted with their inlets around 1.4 m above the ground level. An electric valve was used to alternate sampling between room #1 and room #2 (Fig. 3.4). The NH_3 Analyzer was self-equipped with a sampling pump and drew air from the manifold at 600 cc/min. The analyzer was connected to a data logger (Model CR 1000, Campbell Scientific, Logan, Utah, USA) to automatically record the data. The averaging time for the analyzer was set as 300 s (5 min), and the data logger recorded the averaged data every 30 min. That is to say, the average ammonia concentration was recorded hourly for each room. The NH_3 Analyzer was calibrated every week with a 10 ppm NH_3 calibration gas and tanked clean air (0 ppm) to check for possible drift.

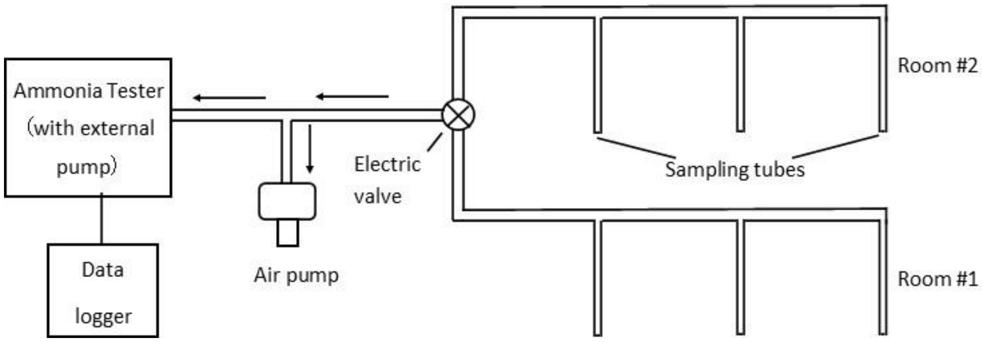


Figure 3.4. Schematics of air sampling for ammonia concentration measurement in sow gestation rooms

3.3.2.2 Temperature and relative humidity

Temperature and relative humidity were continuously measured using 3 temperature sensors (T-Type Thermocouples, Honeywell, Charlotte, North Carolina, USA) and 3 humidity sensors (Model HIH-4602 sensors, Honeywell) in each room. The sensors were mounted at the same locations as the ammonia sampling points in Fig. 3.1, but 0.3 m higher. The sensors were also connected to the data logger (Model CR 1000, Campbell Scientific, Logan, Utah, USA) with recordings every 5 minutes.

3.3.3 Assessing the cleanliness of the slatted floors

The entire floor of each room was visually inspected to identify the established dunging areas in the first two weeks and a floor map was then drawn to indicate the dunging areas. Two time-lapse cameras (Pentax Optio W80, 5× wide angle zoom (28-140 mm); Pentax Ricoh Imaging Americas Corporation, Denver, CO) were mounted on the ceiling in the corners adjacent to the walkway to take pictures of the pen floor area every hour. Cameras were set to automatically take time-lapse pictures every Tuesday from 7 a.m. to 7 p.m. based on the lighting schedule in barn. The floor of each room would be scraped clean of manure every Wednesday.

MIPAR^{TM} image processing software (Sosa et al., 2014) was applied to analyze the time-lapse pictures. According to the observation of sow activities, the slatted floor in each room was divided into four areas for analysis: sleeping, low traffic, high traffic and dunging areas (Fig. 3.5). Firstly, a rectangle on the exposed floor surface of each area was drawn for the image analysis by MIPAR^{TM} and the picture was set to grayscale color. Then the manured area of the floor was marked as red color by using the “adaptive threshold” function in “segmentation”.

However, because the color of the gaps between the slats was close to black, which could be misidentified as the manured area. The gaps were removed from each rectangle manually by using “manual edit function”. Finally, the percentage of manured floor area including gaps blocked by manure were calculated by the “area fraction” function in “measurement” for the evaluation of floor cleanliness. The percentage of manured area of the whole floor was determined by averaging the four area fractions.

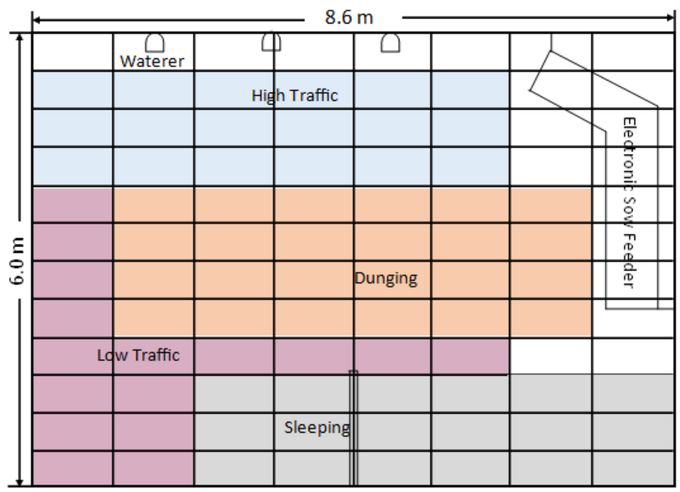


Figure 3.5. The plan view of the pen with four floor areas based on the observation of sow activities: sleeping, low traffic, high traffic and dunging areas

3.3.4 Assessing the cleanliness of sows

From the time-lapse photos (Pentax Optio W80, 5× wide angle zoom (28-140 mm); Pentax Ricoh Imaging Americas Corporation, Denver, CO), the cleanliness of animals was also analyzed by MIPAR^{TM} image processing software (Sosa et al., 2014) with the same procedure. The strips painted on the back of sow in different colors could be misidentified as contaminated area, therefore, the strips were removed manually by using “manual edit function” as well. Four anatomical areas of sow: rear, back and both flanks were evaluated as shown in Figure 3.6. The percentage of manured area of sow’s body was determined by averaging the four area fractions. The cleanliness of animals in the two gestation rooms may be influenced by room temperature, air quality and humidity, which can change over time. Therefore, to accommodate comparisons between the two rooms, sow cleanliness in both rooms were assessed on the same days.

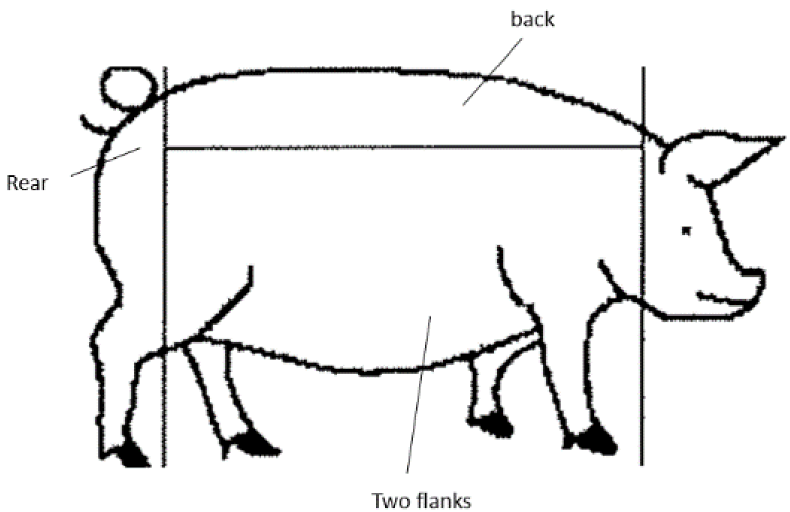


Figure 3. 6. The anatomical areas of sow used for cleanliness evaluation (Minvielle & Le Roux, 2009)

SAS software (version 9.3; SAS Inst. Inc., Cary, NC) was used in this study for statistical analysis. The mean values and standard deviations were calculated by univariate analysis in SAS, and times series were compared using paired t-test between the two floors of two gestation rooms. A probability level of $P \leq 0.05$ was chosen as the limit for statistical significance in all tests.

3.4 Results and discussions

3.4.1 Indoor air quality

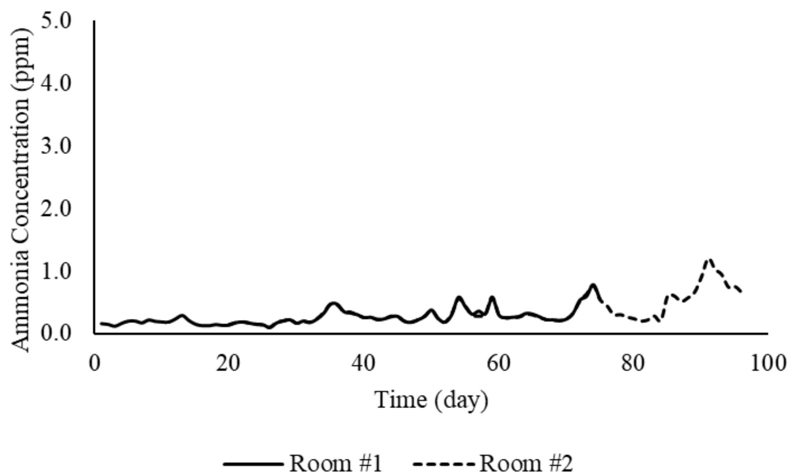
The average values and standard deviations of temperature and humidity for the two rooms during two gestation cycles are summarized in Table 3.1. Generally, the average temperature and relative humidity of the two rooms were almost the same in both gestation cycles. This confirmed that the two rooms were indeed identical in terms of physical dimensions and climate conditions. The average temperatures of two rooms for gestation cycle 1 were around 4 °C higher than gestation cycle 2 because the cycle 1 occurred from June to October (summer and fall) with average outdoor temperature of around 20 °C and cycle 2 from November to February (winter) with average outdoor temperature of about -20 °C. Moreover, the standard deviations for temperature and humidity in cycle 1 were higher than cycle 2, which meant that temperature in cycle 1 varied more than that in cycle 2 due to higher ventilation rates in the summer and fall months.

Table 3. 1. Average values and standard deviations of ammonia concentration, temperature and relative humidity in the two sow gestation rooms with different slat to slot ratio of slatted concrete floor

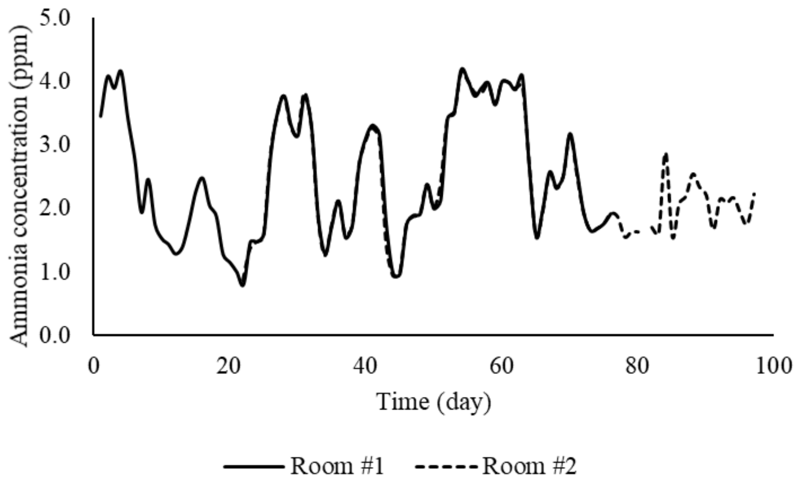
Room	Ammonia concentration (ppm)		Temperature (°C)		Relative Humidity (%)	
	Mean	SD	Mean	SD	Mean	SD
Cycle 1						
Room #1	0.26	0.16	23.4	3.1	67.8	11.3
Room #2	0.36	0.25	22.4	3.0	66.8	11.5
Cycle 2						
Room #1	2.49	1.06	18.2	0.7	70.0	4.1
Room #2	2.46	0.97	18.9	0.8	64.7	6.3

The ammonia concentration fluctuated every day in both rooms during the two cycles (Fig. 3.7). The ammonia concentration of room #1 for test cycle 1 ranged from 0.04 to 1.24 ppm with the mean value of 0.26 ppm, and from 0.48 to 5.93 ppm with the mean value of 2.49 ppm for cycle 2. The ammonia concentration of room #2 for cycle 1 varied from 0.04 to 1.41 ppm with the mean value of 0.36 ppm, and from 0.50 to 6.13 ppm with the mean value of 2.46 ppm for cycle 2. The ammonia concentration in cycle 2 (on average 2.49 ppm in room #1 and 2.46 ppm in room #2) was generally higher than cycle 1 (0.26 ppm in room #1 and 0.36 ppm in room #2) (Table 3.1), which was attributed to higher outdoor temperature and ventilation rates in cycle 1 than cycle 2. The ventilation rates in summer and fall months were considerably higher than the winter months to maintain the appropriate indoor temperature and relative humidity.

The measured ammonia levels in two cycles in both rooms were much lower than the commonly recognized threshold of 20 ppm (Commission Internationale de Genie Rural, 1984). The measured ammonia levels in this study were also much lower than those reported in the literature. Seedorf and Hartung (1999) investigated the ammonia concentrations in several German livestock buildings and found the highest mean concentration of 15±9 ppm in fattening pigs and 13±4 ppm in sow buildings. Ni et al. (2000) observed that the average daily ammonia concentration at a mechanically ventilated swine barn was 5.6±0.41 ppm with a range from 2.8 to 10.6 ppm. The low ammonia concentrations in this study were mainly attributed to the large rooms used in the experiment. Even though the (floor) space allowance for sows was 2.2 m^2/ sow meeting the standards from the Canadian Code of Practice (National Farm Animal Care Council, 2014), each room contained two pens and only one pen was used for testing as shown in Figure 3.1. In other words, there was twice as much space for ammonia to "dilute" in the test room compared with a fully stocked room.



(a) Cycle 1



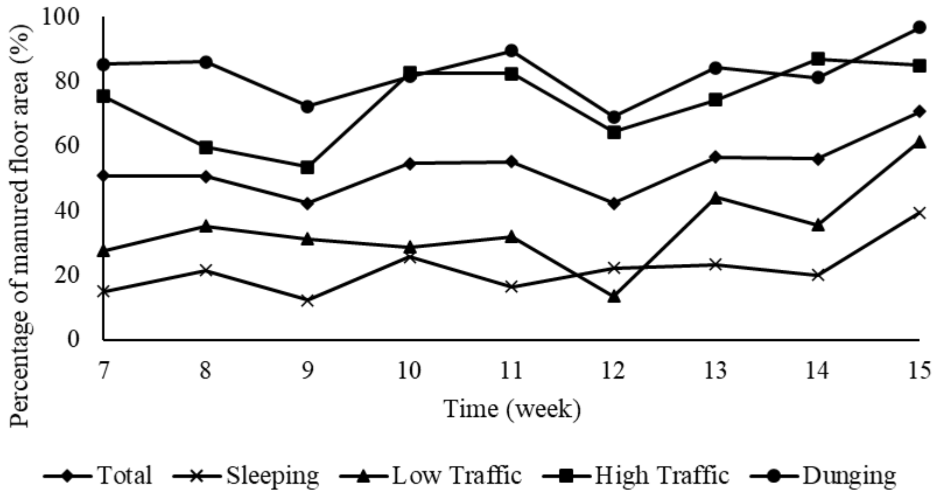
(b) Cycle 2

Figure 3. 7. Variation of ammonia concentration with time in two test rooms with different slat to slot ratios of slatted concrete floor during two sow gestation cycles

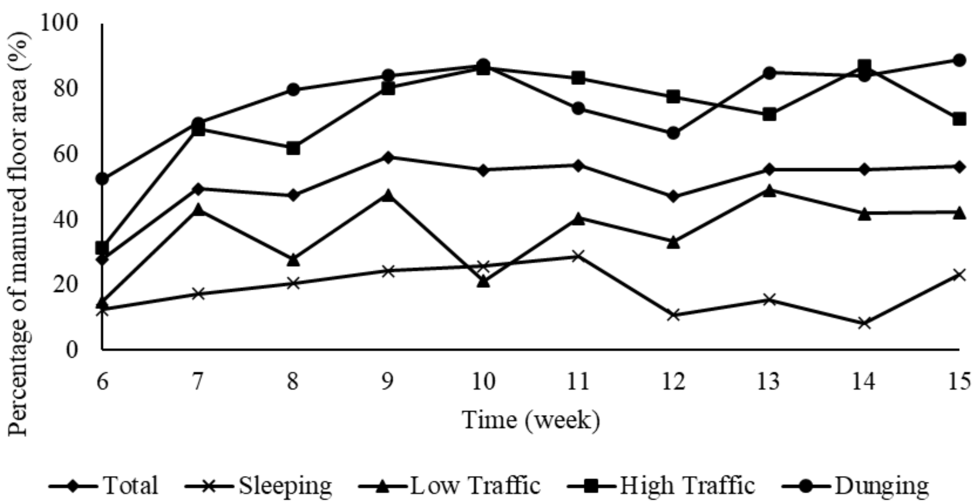
Further statistical analysis indicated that there was no significant ($P>0.05$) difference in ammonia concentration between the two gestation rooms with different floor configurations. In other words, the narrower slats (105 mm) and slots (19 mm) did not have any negative effect on the indoor air quality in comparison with the commonly used 125 mm & 25 mm (slats & gaps) floor. Aarnink et al. (1997) arrived at a similar conclusion that the ammonia emission for a concrete floor with 100 mm slats and 20 mm gaps was almost the same as a concrete floor with 70 mm slats and 18 mm gaps.

3.4.2 Cleanliness of slatted floor

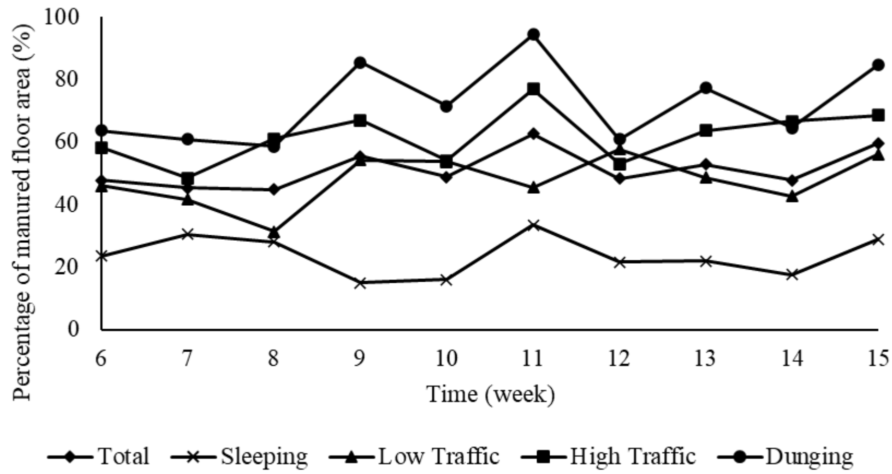
Generally, the sleeping area has the lowest manure coverage and the dunging area was the most befouled (Fig. 3.8). On some occasions, for example, week 14 of cycle 1 in room #1, the high traffic area appeared to have more manure coverage than dunging areas. A close examination revealed that the high traffic area was close to the waterers, so some of the wet area was from drinking water rather than from urine. During gestation cycle 1, the dunging and high traffic area showed a slight peak of manure coverage at week 11 for room #1 and week 14 for room #2 (same timeline) which had the highest ambient temperature of the summer. According to Aarnink et al. (2001), at high ambient temperatures, especially in combination with high pig weights, pen fouling is difficult to prevent without any additional measures. Figure 3.8 also shows a slight upward trend of every plot. For gestation cycle 1, the manure coverage of the total floor area increased from 50.78% to 70.58%, and from 27.77 to 56.25% in room #1 and #2, respectively; for gestation cycle 2, the total floor area had manure coverage increasing from 47.86% to 59.57%, and from 51.22 to 57.41% in room #1 and #2, respectively. In other words, the floor had more manure coverage as time progressed, even with weekly floor cleaning. Some manure could still remain on the slatted surface after the floors were scraped clean every week.



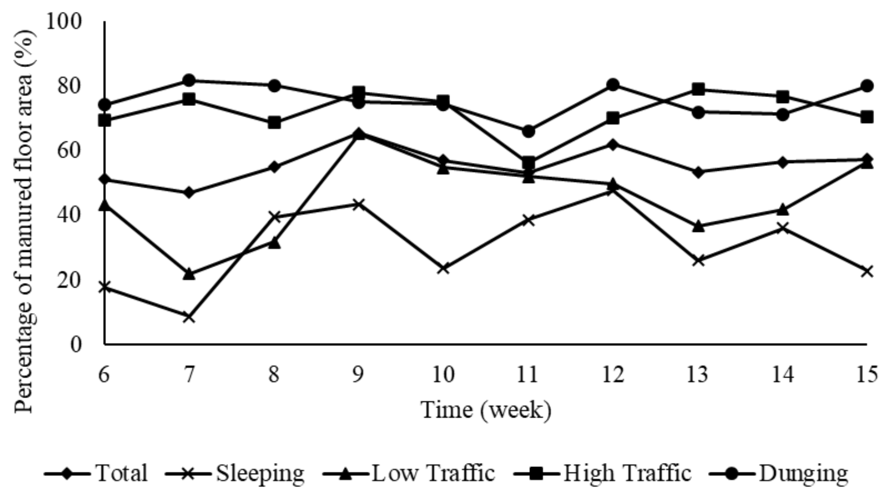
(a) Room #1 (Cycle 1)



(b) Room #2 (Cycle 1)



(c) Room #1 (Cycle 2)



(d) Room #2 (Cycle 2)

Figure 3. 8. The percentage of manured area on the slatted floor in two test rooms and two gestation cycles

On average, the percentages of befouled floor area in room #1 were 53.14% in gestation cycle 1 and 51.34% in cycle 2, respectively. In room #2, 50.92% of the floor area and 55.83% of the floor area were covered by manure in cycle 1 and cycle 2, respectively (Table 3.2). There was no significant difference in the average percentages of floor area covered by manure between the two rooms (P>0.05). This meant that the 105 mm slat & 19 mm gap floor had the same performance as the 125 mm slat & 25 mm gap floor for manure drainage. This result agreed with the observations of Aarnink et al. (1997) and EFSA (2005). Aarnink et al. (1997) did not find any significant difference in wetted surface of the slats after urination for a floor with 100 mm slats and 20 mm gaps compared to a floor with 70 mm slats and 18 mm gaps. EFSA (2005) compared concrete floors with gap width of 18 and 20 mm to floors with slat widths of 67, 70, 75 and 91 mm. The permeability of the floors was between 16 and 20%. They found no differences on hygiene and pen fouling.

Table 3. 2. Average percentage of manure befouled area on the slatted floors in two rooms with different configurations

Room	Average percentage of manured floor area (%)									
	Total		Sleeping		Low Traffic		High Traffic		Dunging	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Cycle 1										
Room #1	53.14	8.50	21.75	7.87	34.39	13.01	73.70	12.01	82.73	8.37
Room #2	50.92	9.12	18.65	6.91	36.12	11.49	71.82	16.41	77.10	11.51
Cycle 2										
Room #1	51.34	6.07	23.66	6.36	47.80	8.07	61.72	8.51	72.19	12.60
Room #2	55.83	5.23	30.40	12.48	45.40	12.91	71.98	6.70	75.54	5.01

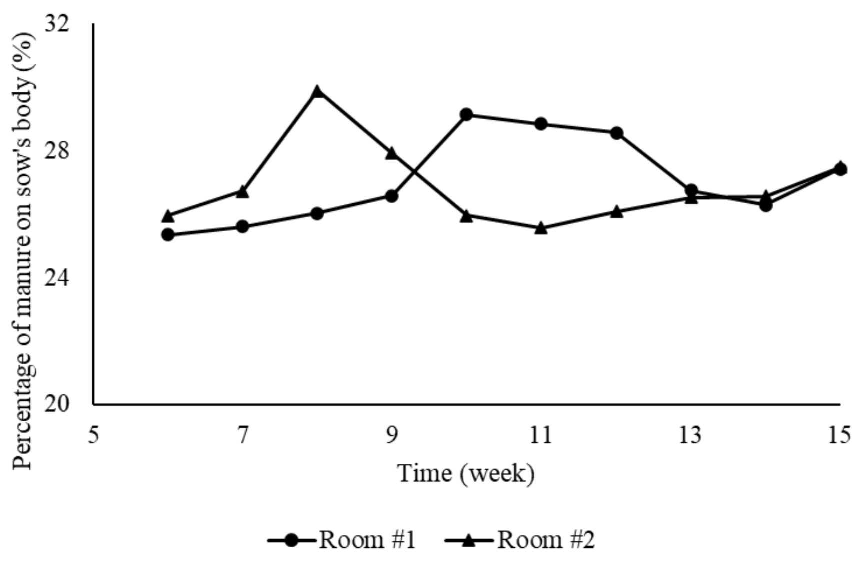
3.4.3 Cleanliness of sows

The percentages of sow body area covered by manure in two rooms are shown in Table 3.3. In gestation cycle 1, the average percentage of manured body area was 27.05% in room #1 and 26.87% in room #2, respectively. In gestation cycle 2, every sow in room #1 had 26.93% average body area covered by manure and had 27.08% manured body area in room #2. However, there was no significant difference in the percentages of animal’s body area covered by manure between the two rooms ($P>0.05$). Minvielle and Le Roux (2009) used a five-point visual scoring method (score 0: no visual contamination; score 1: < 25% of body surface considered dirty; score 2: 25%-50% surface considered dirty; score 3: 50%-75% surface considered dirty; score 4: > 75% surface considered dirty) to assess the cleanliness of pigs, and scored 40% of the pigs as 0 or 1, 20% of them as 2, and the rest as 3 or more. They considered the pigs relatively clean. Accordingly, the sows in this study were considered clean.

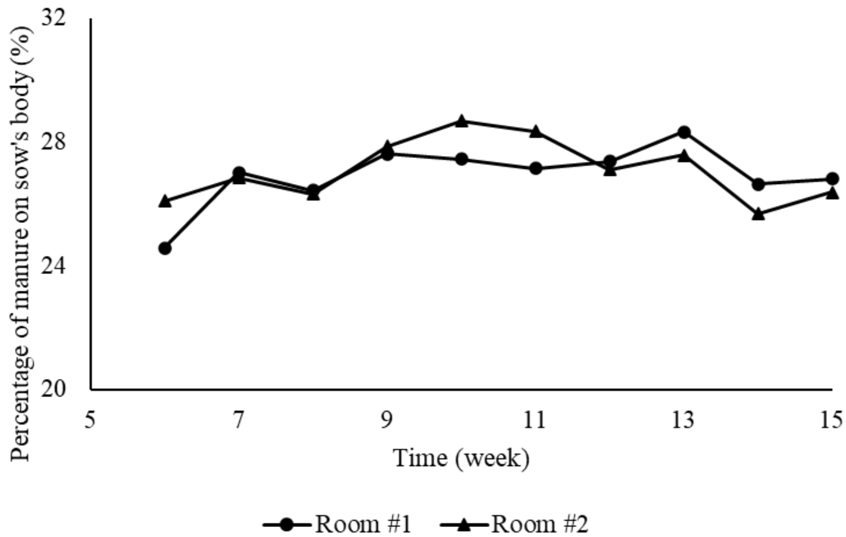
Table 3. 3. Average percentage of manure soiled area on sow's body in two sow gestation rooms and two gestation cycles

Room	Average percentage of manured sow body area (%)	
	Mean	SD
Cycle 1		
Room #1	27.05	1.37
Room #2	26.87	1.28
Cycle 2		
Room #1	26.93	0.99
Room #2	27.08	1.00

Figure 3.9 shows the average percentage of contaminated surface of sow's body in two rooms and two gestation cycles, as a function of the gestation week. The plots for the two rooms were close to each other. In cycle 1, the percentages of manured body area from week 10 to 12 in room #1 and from week 7 to 9 in room #2 were obviously higher than other weeks. The possible reason was because the temperature was the highest (around 24 °C) in those weeks and pigs preferred lying on the floor to cool off when the environment was warm (Aarnink et al., 1997).



(a) Cycle 1



(b) Cycle 2

Figure 3. 9. Comparison of percentage of manured sow's body surface between two rooms

3.5 Conclusions

The 105 mm slat & 19 mm gap floor, which was optimal for the welfare of gestating sows, had the same performance as the commonly used 125 mm slat & 25 mm gap floor in terms of manure drainage and air quality. The floors of both configurations had slightly increased manure coverage as time progressed, even with weekly floor cleaning. The indoor ammonia level was higher in the winter months than in the summer and fall months for both floor configurations.

4. In-barn Measurement of Surface Roughness and Friction of Slatted Concrete Floors in Sow Gestation Rooms

4.1 Abstract

Claw injuries of pigs due to inadequate floor surface conditions are a major concern in pig operations. Rough and slippery concrete floor surfaces can result in claw disorders. In this paper, the surface roughness and dynamic coefficient of friction (DCOF) of concrete floors used in two sow gestation rooms were studied. The first room had a slatted concrete floor with 105-mm wide slats and 19-mm wide gaps, and the second room had a floor with 125-mm wide slats and 25-mm wide gaps. A portable tester was designed and built to measure the surface roughness and friction of concrete floors. Measurements were conducted weekly during two gestation cycles for a total of 21 weeks. Based on the observations of sow activities, the floor in each room was virtually divided into four areas, namely dunging, high traffic, low traffic and sleeping areas. Surface roughness and friction were measured in the four areas in directions both parallel and perpendicular to the slats. The results showed that the length of time of floor usage by sows had a significant effect on the roughness and DCOF of concrete floors, with a sharp reduction in the DCOF after the first two weeks of use because manure stuck in the pores of the concrete surface reduced the interlocking between the asperities of the contact surfaces. No significant differences in the roughness and DCOF were found among different areas of floor (dunging, high traffic, low traffic and sleeping) or between the two floor configurations in the first 21 weeks of floor usage.

Keywords: Sow barn, Slatted concrete floor, Surface roughness, Friction.

4.2 Introduction

Slatted concrete floors are widely used in pig barns due to their durability and easy manure removal. Inappropriate floor properties in pig barns are considered to be a major cause of lameness and claw injuries (Gjein & Larssen, 1995a; Lahrmann et al., 2003). The claw injuries could be caused by rough surfaces of concrete floor due to abrasion or by slipperiness of floor (Gjein & Larssen, 1995b; McDaniel & Wilk, 1991). Floor friction is an important indicator of the floor conditions, affecting the interaction between the pig foot and the floor (Webb & Nilsson, 1983). The dynamic coefficient of friction (DCOF), defined as the ratio between frictional force and normal force acting on an object while the object is moving, has been widely used as a measure of floor slipperiness (Chang et al., 2001). Slip occurs when the coefficient of friction is too low at the claw-floor interface (van der Tol et al., 2005). Generally speaking, the DCOF is related to surface roughness of the floor (Chang et al., 2001), i.e., the smoother the surfaces are, the lower DCOF, and the more slippery the surfaces. Insufficient friction between the foot and the floor, which leads to slipping on the floor, may affect pig gait (Li et al., 2004; von Wachenfelt et al., 2008). The floor DCOF values differ for different floor conditions (wet or dry) of the same floor, and even for different methods of measuring floor friction (Phillips & Morris, 2001; Webb & Nilsson, 1983).

In most floor friction studies reported in the literature, the concrete floor samples were tested in laboratories with simulated in-barn situations. For example, Franck et al. (2007) used a drag method described by Nilsson (1988) to assess the DCOF and static coefficient of friction (SCOF) of both dry and wet concrete floors. The results showed that the DCOF in wet conditions was larger than in dry conditions, and the DCOF and the average roughness had positive but low correlations. Franck and De Belie (2006) tested five concrete floors with different surface structures obtained by using different finishing methods. It was found that the roughest surface was the concrete heavily sandblasted (average roughness: 0.488 mm) and the smoothest was the one finished with a metal float (average roughness: 0.062 mm). However, floors in pig barns are subject to not only pig traffic but also the corrosive effect of manure. Furthermore, these effects of pig traffic and manure exposure are not uniform throughout the barn because pigs often "compete" for space in relatively small areas, where the floors could be wet and fouled, leading to higher levels of degradation (De Belie, 1997b). Little information was found in the literature on the in-situ surface properties of slatted concrete floors in actual pig barns.

This study was designed to quantify the roughness and DCOF of newly fabricated concrete slatted floors in a barn when the floors were being used by gestating sows. The specific objectives of this study were to determine: (1) the relationship between frictional properties and time of use, and (2) surface properties of floor at different locations in the barn. It should be noted that the focus of this study was the initial changes in floor friction of new concrete floors without considering long-term chemical attacks.

4.3 Method and materials

4.3.1 Concrete floors and test rooms

The tests were carried out in the Swine Research Unit at the Glenlea Research Station, University of Manitoba. Two new fully slatted concrete floors were designed, manufactured and tested in two gestation rooms (Barkman Concrete Ltd., Steinbach, MB, Canada). Floor #1 had 105 mm wide slats and 19 mm wide gaps (room #1) and floor #2 had 125 mm wide slats and 25 mm wide gaps (room #2). These two slatted floor configurations were selected based on a kinematics study that indicated that the 105 mm slat/19 mm gap configuration was the best in terms of sow gait characteristics compared with other seven floor configurations (Devillers et.al, 2019), while the 125 mm slat/25 mm gap configuration is most commonly used in the pig barns in North America.

The concrete floors were manufactured using a semi dry mix with a water to cement ratio of 0.51. The coarse aggregates were made up of Carbonate rock (68.7%) and Granitic rock (27.6%). About 65%-75% of the coarse aggregates were smooth and rounded, and the rest were crushed. The fine aggregates were made up of Silicate rocks (81.5%) and Carbonate rocks (18.2%). The fine aggregates were all smooth and rounded. The floor surface was brush (broom)-finished.

The slatted concrete floors were installed in two rooms covering the whole floor area (i.e., the floors were fully slatted in both rooms). The two rooms were identical in dimensions, 8.6 m in length and 6.0 m in width (Fig. 4.1). Each room housed 24 pregnant sows, with a gross floor allowance of 2.2 m^2/sow. Each room was equipped with an electronic sow feeder (NEDAP, New Standard Ag Inc., Saint Andrews, MB), and three automatic waterers (water bowl) (Fig. 4.1).

The indoor temperature and relative humidity (RH) of the two test rooms were maintained the same, around 20 °C and 65%-70% RH, respectively. Tests were conducted from gestation week 5 to week 15 covering two gestation cycles (for more details, see Devillers et al., 2020). Following the commonly used practice on farm, the slatted floors of both rooms were cleaned by high pressure washing between the gestation cycles. The floor in each room was visually inspected to identify the established dunging area(s) and other pig activities (feeding, drinking, resting, etc.) were also observed in the first two weeks to determine the floor use patterns by pigs. The floor inspections were conducted in-person weekly and by viewing images recorded by two time-lapse cameras mounted on the ceiling. The cameras were set to automatically take time-lapse pictures every Tuesday from 7 a.m. to 7 p.m. based on the lighting schedule in the rooms. During each inspection, manure accumulation and sow movement on the floor were visually assessed. Based on image viewing and confirmed by in-person observations, four distinctive areas were identified: (a) a sleeping (lying) area near the partition panel, which was relatively clean; (b) a dunging area where more manure was observed than other areas; (c) a high traffic area where more sow movements were observed; and (d) a low traffic area close to the sleeping area. More pigs were found to move around in the high traffic area close to the waterers. The dunging area near a hung chain for environmental enrichment had more manure coverage than other areas. Also, both high traffic and dunging areas visually appeared wet. Specifically, a thin layer of wet manure remained on the concrete surface after scraping, while the low traffic and sleeping areas were relatively dry. Based on the observations, the whole floor in each room was virtually divided into four areas: dunging, high traffic, low traffic, and sleeping areas for conducting measurements. One floor panel (about 1.0 × 0.5 m) was selected for each of the four areas to conduct surface roughness and friction measurements and the measurements were taken in the directions parallel and perpendicular to the slats (Fig. 4.1).

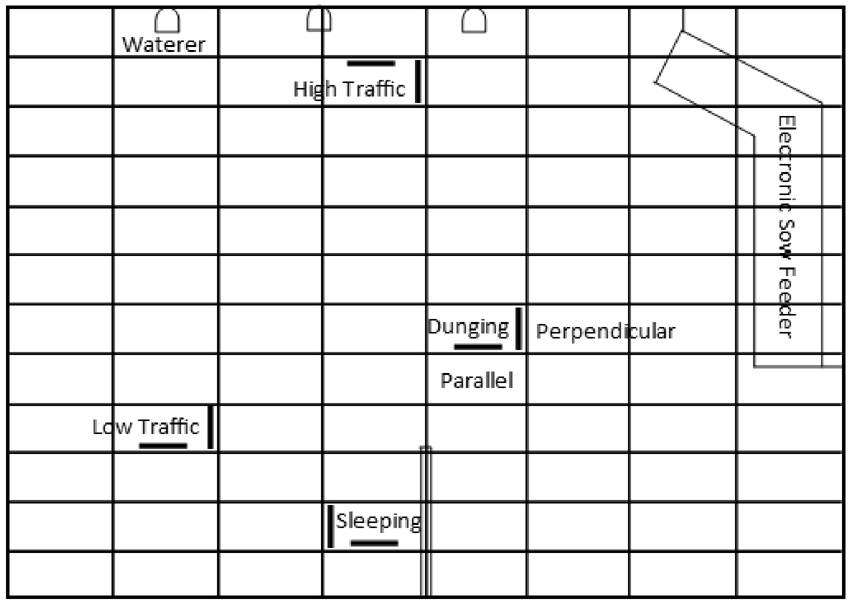


Figure 4. 1. Illustration of different areas (dunging, high traffic, low traffic and sleeping area) where surface properties were measured in a sow gestation room

4.3.2 Measurements of floor friction

A portable surface tester was designed and built to measure the surface roughness and friction of the slatted concrete floors (Figure 4.2). The tester frame consisted of a carriage that could move along a 483 mm path at a constant speed of 0.7 mm/s. The carriage movement was driven by a stepper motor and screw gear assembly either forward or backward along the 483-mm path. The tester frame was supported by 4 adjustable feet for levelling the moving track on uneven surfaces.

Friction between animal feet (hoof) and concrete is dictated by the properties of both the hoof and the concrete. A 50 × 25 mm piece of high-density polyethylene (HDPE) was used to simulate a sow foot (Fig. 4.2). Nilsson (1988) and Beer (1976) used polyethylene in friction tests and showed that HDPE had approximately the same coefficient of friction as the dry hoof. The HDPE foot was mounted on the carriage and could slide over the test floor surface along the 483-mm path in both forward and backward directions (Fig. 4.2). A constant vertical (normal) force of 102 N (dead weight of 10.3 kg) was applied on the test foot and the horizontal pulling (friction) force was measured by a load cell (LCEB-50, Omega Engineering Inc., Norwalk, CT, USA) through which the foot was mounted on the carriage (Fig. 4.2). It should be noted that the magnitude of this vertical force (102 N) was relatively low in comparison with the animal weight because the friction tester had to be light enough to be portable (by a person) and powered by a battery pack in barns. In other studies reported in the literature, dead loads close to animal weight were commonly used. However, theoretically speaking friction coefficient is independent of the vertical (normal) force. Nilsson (1988) reported that for hard materials there were no significant differences between the coefficients of friction obtained with different normal forces. Hence, a light weight (102 N) was used to achieve the portability required in-barn testing.

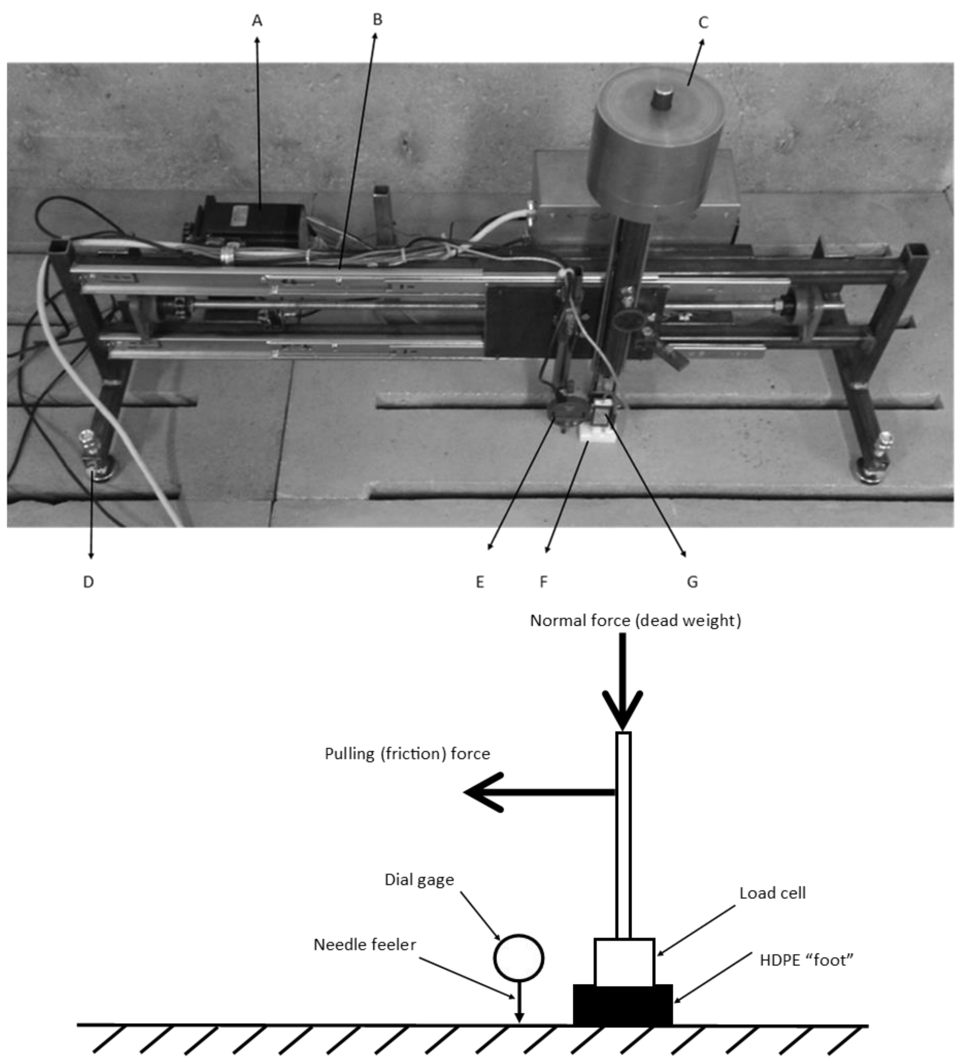


Figure 4. 2. Photograph and schematics of the portable surface tester for in-barn measurement of floor friction and surface roughness (A: stepper motor; B: carriage; C: dead weight; D: adjustable feet; E: Dial gage; F: HDPE “foot”; G: load cell)

For each test, the test foot slid over the 483-mm path in both forward and backward directions. For each direction of travel, 690 readings of frictional force were taken. The coefficient of friction (COF) measured in this study using the "drag method" is considered as dynamic COF (DCOF), which is related to the risk of slips at the start of the supporting limb phase, where the hoof is gaining contact with the ground (Phillips & Morris, 2000). The dynamic coefficient of friction (DCOF) was calculated from measured forces by the following equation.

$$\mathrm{DCOF} = \frac{F_k}{F_n} = \frac{F_k}{mg} \tag{4.1}$$

where,

F_k= pulling (friction) force, N;

F_n= normal force or load, N;

m= dead weight applied on the test foot, kg;

g= acceleration due to gravity, m/s^2.

Friction tests were conducted after weekly scraping of the floors to remove accumulated manure. A plastic snow pusher was used to remove the accumulated manure on the slatted floor, following the method used in the normal barn operation. The floor was scraped until no loose manure was visible on the floor. It should be noted that some studies reported in the literature kept manure on the concrete when measuring friction. If the surface is fouled with manure, a layer of manure exists between the contact surfaces acting as a lubricant. The focus of this study was on the changes in concrete and, therefore, it was decided to measure friction after the floor was scraped to ensure the consistency of floor property measurements among different areas. In other words, the effect of manure accumulation was purposely excluded otherwise measured friction would reflect the effects of both concrete changes and manure lubrication. In addition, the manure that remained on the floor surface could lead to difficulties of conducting measurements because large chunks of dry (stiff) faeces could stop the carriage unit from moving.

The tests of the two floors started on different dates, as indicated by the normal barn flows. Table 4.1 shows the test schedule during two gestation cycles of the sows. In each test, friction was measured both parallel and perpendicular to the slat direction at each of the four locations (Fig. 4.1). Parallel tests were run on the slats, while perpendicular tests were run along the girder portions of the slats.

Table 4. 1. In-barn test schedule and corresponding gestation weeks of sows

Total time of floor usage (week)	0	1	2	3	5	7	9	13	17	21
Gestation week	-	6 (C1)	7 (C1)	8 (C1)	10 (C1)	12 (C1)	14 (C1)	7 (C2)	11 (C2)	15 (C2)
Floor #1	✓		✓		✓	✓	✓	✓	✓	✓
Floor #2	✓	✓		✓	✓	✓	✓	✓	✓	✓

Note: C1=gestation cycle 1; C2=gestation cycle 2; ✓= a test was conducted.

4.3.3 Measurement of surface roughness

The roughness of the concrete floors was quantified by measuring the height of the surface asperities (peaks and valleys) with a digital dial gauge (543-792B, Mitutoyo Canada Inc, Mississauga, ON, Canada), which was mounted on the tester carriage and the tip of the dial gauge “slid” over the concrete surface during testing (Fig. 4.2). The dial gauge tip was fitted with a sharp needle feeler for better sensing of small peaks and valleys on the concrete surface. The signal from the digital dial gauge was recorded every second as the tip slid over the 483-mm path. From the recorded data, a 2-D surface profile was generated, and an average line was drawn as the datum. Following ISO 4288 (1996), a Gaussian filter (see Appendix A) was applied to the profile data to remove the waviness and obtain the roughness profile. The surface roughness value was determined as the arithmetical mean of the absolute values of the profile deviations from the average line of the roughness profile (ISO 4287, 1997). The depths of surface asperities (average height from peaks to valleys of surface) were also evaluated from surface profile data by using the “Findpeaks” function of MATLAB (Version 7.1.0.183 (R14), The MathWorks, Inc., Natick, MA, USA). For each test, the dial gauge was pulled over the floor along the 483-mm path in both forward and backward directions. The roughness test was performed every week after the floor had been scraped.

4.3.4 Data analysis

The coefficient of friction for each single test run was calculated (equation 4.1) from the recorded readings from the load cell. Each test run generated four sets of readings: combination of forward and backward movements and parallel and perpendicular directions. The data from forward and backward movements were combined as one replicate. The statistical analyses were carried out with the software package SAS (version 9.3; SAS Inst. Inc., Cary, NC). The GLM procedures were performed to test the effects of single factor and multiple factors and their interactions (time length of use, floor configuration and activity area). The significance level of 0.05 was chosen in all tests. Also paired t-tests were performed to compare data between the parallel and perpendicular directions and between the “wet” and “dry” floors. The parallel and perpendicular data were combined in the further analysis because no significant differences were found between them.

4.4 Results and discussion

4.4.1 Floor friction

A typical measured friction force-displacement curve is shown in Fig. 4.3. The initial peak indicated the static friction force that needed to be overcome to start sliding. After the initial static force was overcome, the HDPE foot started to slide on the concrete floor under a dynamic friction force required to maintain the sliding motion. Because of roughness of the concrete surfaces, the dynamic friction force fluctuated noticeably. The DCOF was determined based on the mean dynamic friction force over the whole sliding path.

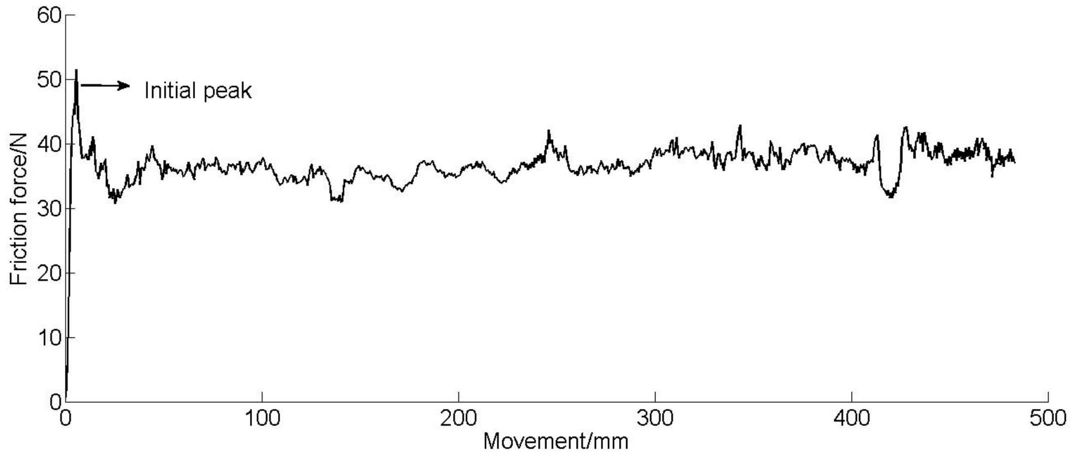


Figure 4. 3. Typical friction force-displacement diagram (parallel test at dunging location of floor #2 in week 0)

The DCOF of the new concrete floor (before it was used) was measured to be 0.36±0.04 (standard deviation), which is comparable with the results of Nilsson (1988) who reported that the DCOF's of new concrete floors were found to be 0.35 and 0.38 at normal loads of 500 and 900 N, respectively. Phillips and Morris (2001) measured the DCOF of concrete floors using cow hooves in a sliding unit to simulate the locomotion of dairy cows and reported the DCOF values to be 0.43 and 0.51 for dry and wet concrete surfaces, respectively. These values were higher than the ones found in this study probably because of using real animal claws instead of HDPE and different concrete surface finishing methods.

Table 4.2 shows that the DCOF decreased sharply after the first use (note: the first set of measurements was taken in week 2 for floor #1 and week 1 for floor #2). On average, the DCOF of floor #1 dropped from 0.36 to 0.17 after the first use, and the floor #2 from 0.36 to 0.16, and the DCOF remained relatively constant thereafter. There was no significant difference ($P>0.05$) in DCOF between the two rooms (two floor configurations). This meant that floor configuration was not a contributing factor to changes in floor friction.

Table 4. 2. DCOF of different floor areas for floor #1 and floor #2

Total time of floor usage/ weeks	Gestation week (W)	Average DCOF (dimensionless)									
		Floor #1					Floor #2				
		Total	Dunging	High Traffic	Low Traffic	Sleeping	Total	Dunging	High Traffic	Low Traffic	Sleeping
0	-	0.36±0.04	0.35±0.04	0.39±0.11	0.34±0.01	0.36±0.08	0.36±0.04	0.35±0.04	0.39±0.11	0.34±0.01	0.36±0.08
1	6 (C1)	-	-	-	-	-	0.16±0.03	0.16±0.04	0.14±0.04	0.15±0.04	0.17±0.04
2	7 (C1)	0.17±0.07	0.19±0.03	0.18±0.09	0.13±0.05	0.19±0.13	-	-	-	-	-
3	8 (C1)	-	-	-	-	-	0.16±0.02	0.14±0.03	0.20±0.02	0.13±0.03	0.16±0.03
5	10 (C1)	0.16±0.05	0.18±0.03	0.15±0.06	0.13±0.04	0.17±0.09	0.18±0.01	0.17±0.01	0.15±0.02	0.19±0.03	0.19±0.01
7	12 (C1)	0.16±0.03	0.15±0.02	0.17±0.02	0.18±0.07	0.14±0.02	0.17±0.01	0.16±0.01	0.16±0.01	0.17±0.01	0.19±0.03
9	14 (C1)	0.18±0.01	0.19±0.01	0.17±0.02	0.18±0.01	0.16±0.01	0.17±0.01	0.16±0.01	0.15±0.01	0.17±0.01	0.18±0.01
13	7 (C2)	0.22±0.01	0.21±0.02	0.22±0.02	0.24±0.03	0.22±0.02	0.19±0.01	0.22±0.01	0.17±0.01	0.19±0.01	0.19±0.02
17	11 (C2)	0.20±0.01	0.25±0.02	0.19±0.03	0.16±0.01	0.21±0.01	0.20±0.01	0.22±0.01	0.19±0.01	0.18±0.01	0.21±0.01
21	15 (C2)	0.24±0.02	0.24±0.03	0.26±0.02	0.23±0.02	0.22±0.01	0.23±0.02	0.24±0.03	0.22±0.03	0.24±0.02	0.21±0.02

When the DCOF of the "dry" area (low traffic and sleeping) and the "wet" area (dunging and high traffic) were compared by paired t-tests, no significant difference was found. The observation in this study agreed with that of Nilsson (1988), who reported that there was no statistical difference between the DCOF for wet and dry concrete floors (new and worn), while conflicting results have been reported elsewhere in the literature. For example, Phillips and Morris (2000) and Franck et. al (2007) reported that the dynamic coefficient of friction on wet concrete floor was higher than that on dry floor. However, Von Wachenfelt (2009) observed that DCOF of concrete floor was significantly higher in clean (dry) than fouled floor conditions. He used fresh manure on the fouled surface with an average total dry matter content of 20%. In the studies of Phillips and Morris (2000) and Franck et. al (2007), the wet floors were created with a layer of water prior to the tests and then tested with dead claws which were immersed in water overnight. It seemed that different test conditions/methods could lead to different results depending on how the surface is wetted. If the surface is wetted with water, water acts as a lubricant to reduce friction. If the surface is wetted (fouled) with manure, not only water but also a layer of manure (water plus solids) exists between the contact surfaces, which may reduce friction more than water alone. In this study, friction measurements were conducted after the floor had been scraped to ensure the consistency of floor property measurements among different areas. In other words, the effect of manure accumulation was not reflected in this study per se.

The DCOF values reported in this study reflected friction between the simulated animal foot and the concrete floor with no visible layer of accumulated manure in between.

The most significant observation in this study was that the DCOF decreased sharply after the initial use (one to two weeks) (Table 4.2). This sharp decrease might be attributed to two possible reasons: (i) mechanical abrasion of concrete and (ii) the effect of manure stuck in the pores of concrete surface. Given that the sharp decrease was observed in the first week of use in room #2, mechanical abrasion should not have been significant. It is hypothesized here that manure filling of the pore spaces was the main reason for the decrease in floor friction. According to Coulomb's law of friction, frictional force between two contact surfaces is due to the interlocking asperities of the two surfaces. Specifically, as two surfaces come in contact, their asperities go into each other and interlock (Gorb, 2002) (Fig. 4.4a). Manure stuck in the pore of the concrete surface would reduce interlocking (Fig. 4.4b). A simple model of two serrated surfaces was proposed to illustrate interlocking between the simulated animal foot and concrete (Fig. 4.5). In this model, the surface asperities were simply approximated as uniformly distributed teeth of isosceles triangles. The height (D) of the isosceles triangles reflected the average depth of surface asperities and the base interior angle (ϕ) reflected the friction angle (DCOF = $\tan\phi$). For the foot to move horizontally over the concrete surface, it must be lifted over the concrete by a distance of D or sheared along the bottom of the teeth (the A-B line). Let's consider lifting and shearing separately. Work done to lift the foot was N*D and N*d for new and used concrete surfaces, respectively, where d is the smaller pore depth of concrete surface due to manure accumulation. If the friction is proportional to the work done, the ratio of DCOF between the new and used surfaces would be D/d. The shear force required to break a tooth was $2*S*D/\tan\phi*w$ and $2*S*d/\tan\phi*w$ for the new and used surfaces, respectively, where S is the shear strength of the foot material (N/m^2) and w is the width of foot tooth (m). This shows again that the ratio of DCOF between the new and used surfaces would be D/d.

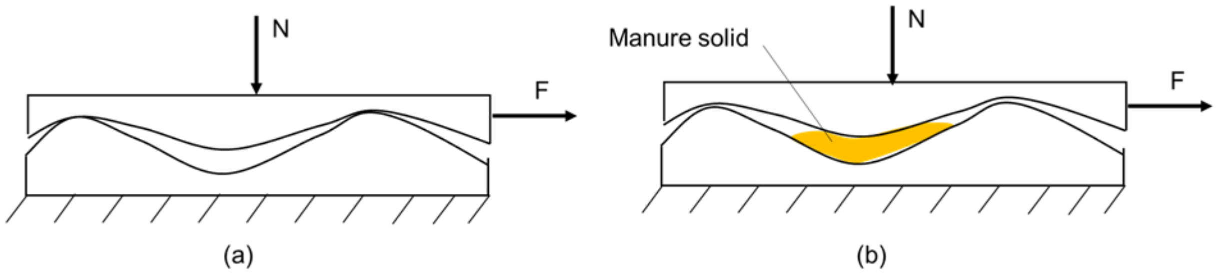


Figure 4. 4. A simplified diagram of interlocking asperities between the test foot and concrete floor surfaces

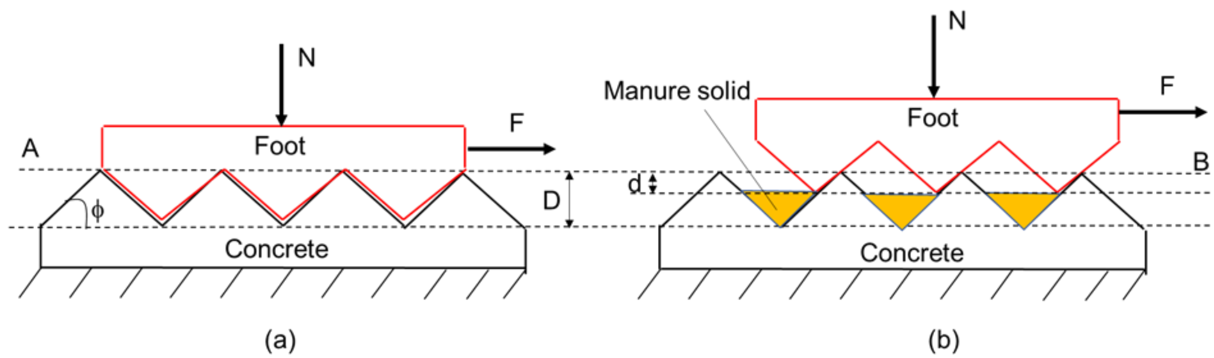


Figure 4. 5. A simple model of two serrated surfaces for interlocking asperities: (a) clean concrete surface; (b) used concrete surface with manure filled in the valleys of concrete surface

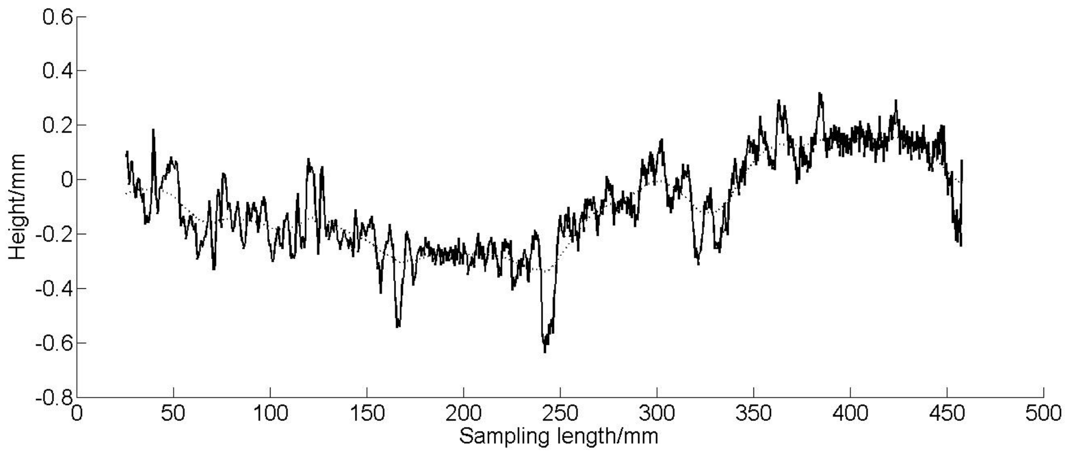
The ratio of D/d and the ratio of friction coefficient (DCOF ratio) between the new and the used floors are shown in Table 4.3. It was found that the D/d ratio (the asperity depth ratio) was lower than the DCOF ratio before week 13, and then became close. Lower D/d ratio indicates higher d value (the asperity depth of used floor). A possible reason why the measured asperities data showed greater values (and thus lower D/d ratios) from week 1 to week 13 compared to the following weeks, could be that the feeler needle used for roughness measurement could penetrate the manure stuck in the pores in the early weeks, which would lead to greater measured asperity depths, or lower D/d ratios. As time progressed, manure accumulated in the pores of concrete surface would become compacted and hard to be penetrated by the feeler needle. In other words, the measured asperity depth after week 13 reflected the true depth of surface pores (asperities) filled with manure.

Table 4. 3. The D/d ratio (calculated from asperity depth) and DCOF ratio between new and used floors during 21-week test period

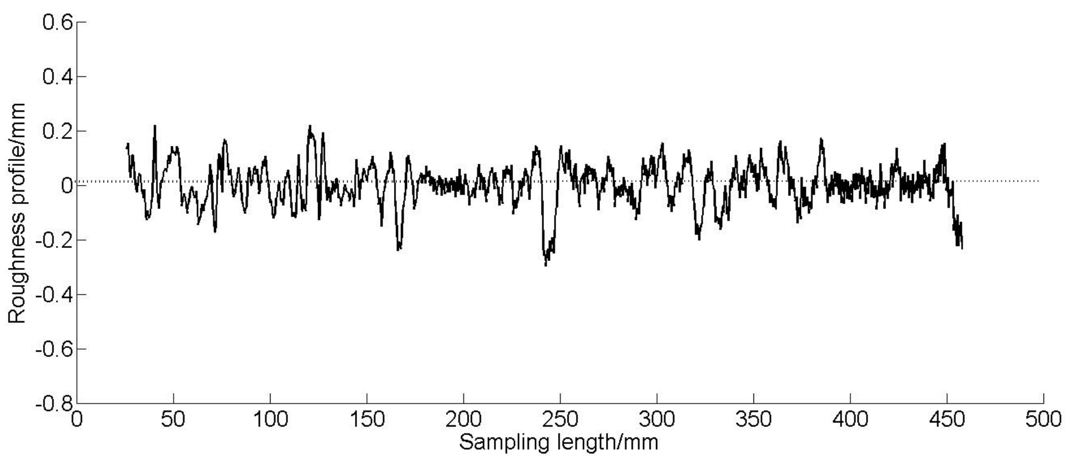
Total time of floor usage/ weeks	D/d ratio			
	Floor #1		Floor #2	
	Asperity depth ratio	DCOF ratio	Asperity depth ratio	DCOF ratio
1	-	-	1.21	2.25
2	1.17	2.12	-	-
3	-	-	1.27	2.25
5	1.24	2.25	1.39	2.00
7	1.30	2.25	1.47	2.12
9	1.30	2.00	1.27	2.12
13	1.56	1.64	1.43	1.89
17	1.47	1.80	1.69	1.80
21	1.63	1.50	1.51	1.57

4.4.2 Surface roughness of concrete floor

Figure 4.6(a) shows a typical 2D surface profile of the floor surfaces tested in this study (variations of the vertical distance measured by the dial gauge along the travel path). The profiles typically exhibited global variations (waviness) and local fluctuations. While waviness reflects the overall flatness of the surface, the local fluctuations indicate the surface roughness (asperities). After removing waviness (Appendix A), the local fluctuations were plotted to represent the surface asperities (Fig. 4.6b). The surface roughness is the average deviation of the roughness irregularities from the mean line. Heights of the surface asperities approximately followed a Gaussian distribution (Fig. 4.7). However, the histogram was slightly skewed towards the negative side (skewness = -0.37), meaning there were slightly more asperity valleys than peaks.



(a) 2D profile



(b) Roughness profile

Figure 4. 6. Surface roughness measurement of dunging area of floor #2 at test week 3

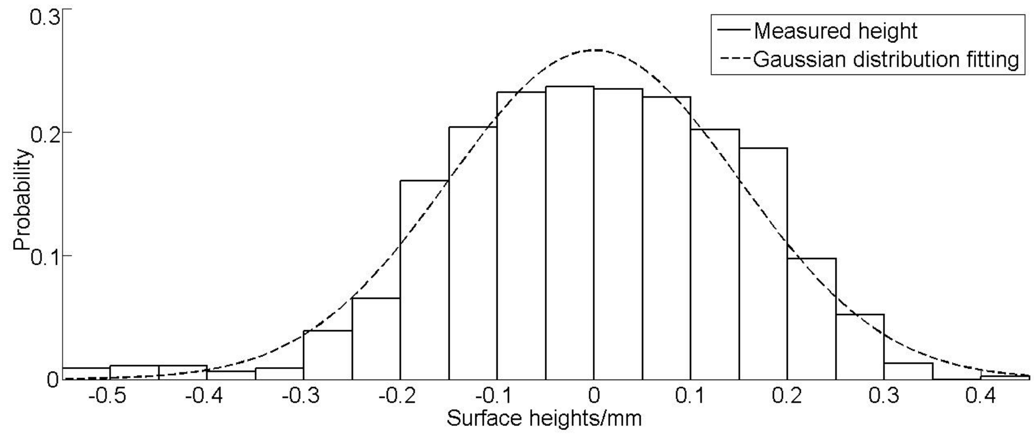
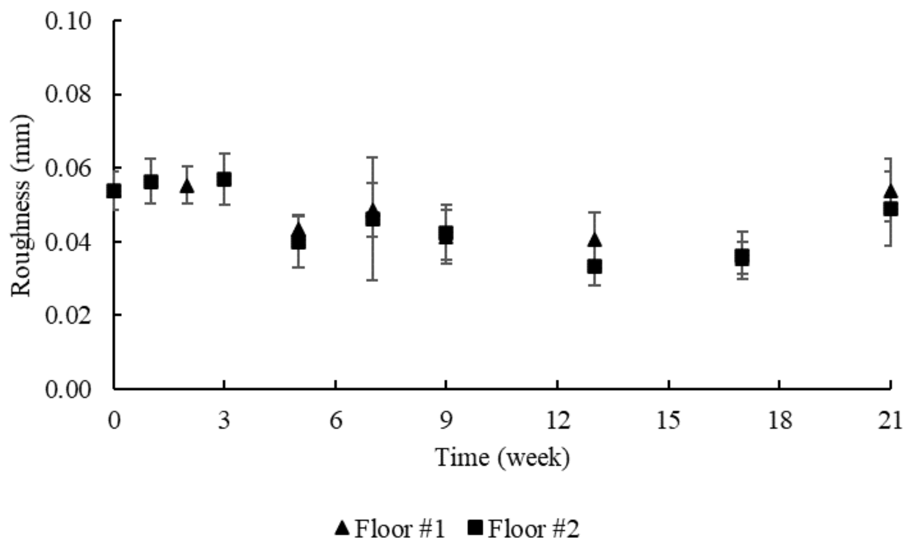


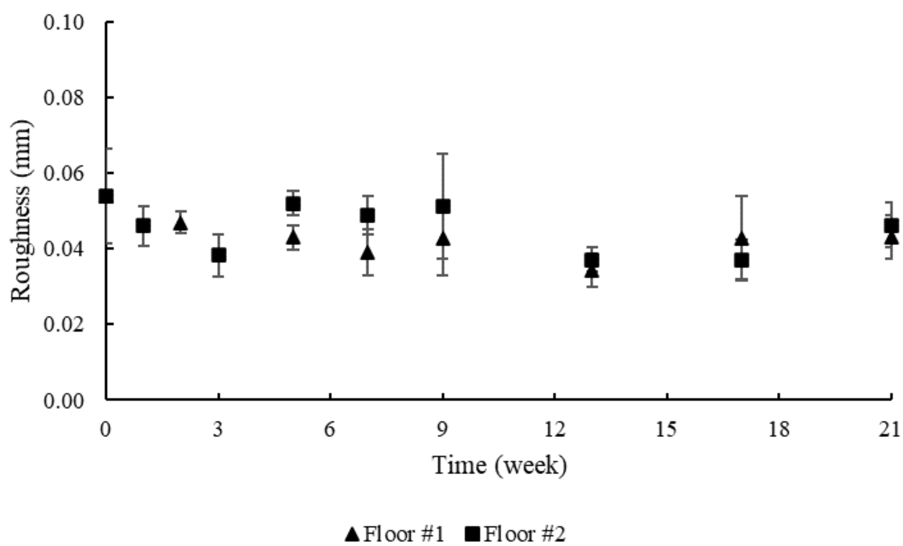
Figure 4. 7. Distribution of surface asperity depths of a tested concrete slatted floor surface

The roughness of new concrete floors (week 0) was determined to be 0.057±0.014 mm, which lies in the roughness range tested by Franck et al. (2007): 0.018-0.145 mm for concrete floor samples finished with a metal float and 0.068-0.213 mm for brush finish.

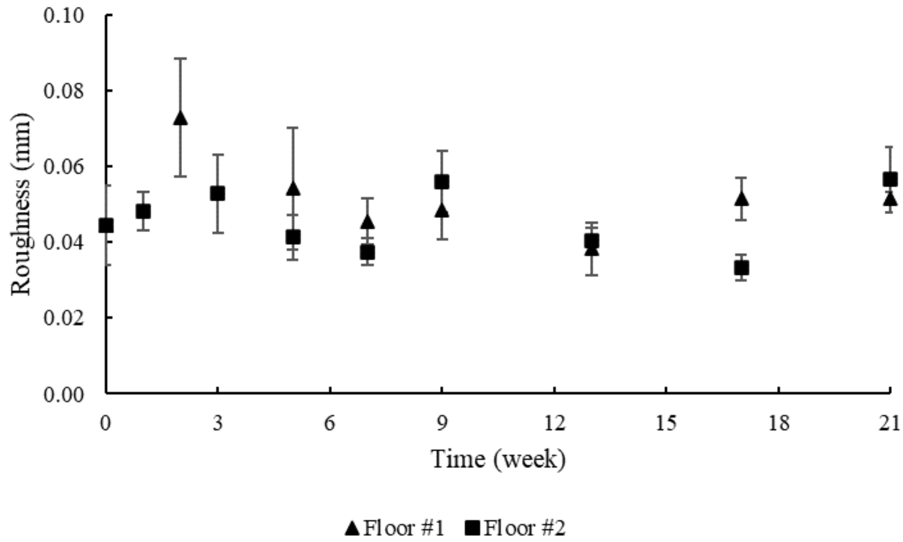
The statistical analysis indicated that the length of time the floor was occupied by sows had a significant effect on the surface roughness ($P<0.05$). On average, the surface roughness decreased from 0.057 to 0.048 mm at the end of test period for floor #1 and from 0.054 to 0.049 mm for floor #2, respectively. But no specific patterns of decrease were obvious (Fig. 4.8). Some floor areas had relatively high surface roughness values at some sampling dates. For example, the roughness of floor #1 (0.073 mm) in the low traffic area for test week 2 was much higher than at other test times. The corresponding standard deviation (0.016 mm) was higher than most of other weeks, indicating the existence of high roughness values. Large chunks of dry faeces remained on the floor could have led to “abnormal” high values of surface roughness. Even the floors were scraped every week before the tests, some faeces could still be left on the floor surfaces.



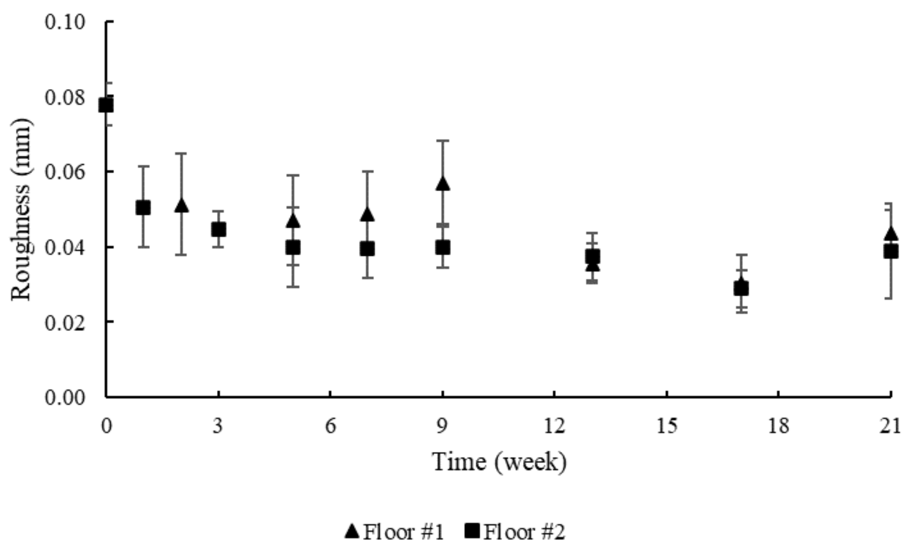
(a) Dunging area



(b) High traffic area



(c) Low traffic area



(d) Sleeping area

Figure 4. 8. Surface roughness of different floor areas for floor #1 ad floor #2 during 21-week test

Researchers, such as De Belie (1997a), have reported that the chemical attack by lactic and acetic acids caused the degradation of the concrete slats, thus increased roughness. However, the test period (21 weeks) in this study was not long enough to observe any effect of chemical attacks on the concrete and the changes in roughness were probably due to accumulation of manure in the concrete pores, as well as some degree of mechanical abrasion.

Statistical analysis showed no significant (P>0.05) difference in surface roughness between test areas. According to De Belie (1997b), the concrete degradation could be expected to be most severe in the region of the feed and water supplies (due to chemical attacks). Given the shortness of the test period in this study, chemical attacks were negligible while animal activities (animal use of floor) were the main cause of surface condition changes. It was observed that the sows spent a lot of time walking and standing in the high traffic and dunging areas because the high traffic area was equipped with waterers and the dunging area had environmental enrichment chains. However, animals spent about the same amount of time if not more lying and sleeping in the low traffic and sleeping areas.

The floor configurations did not cause any significant effect on the roughness (P>0.05). The roughness of two floors showed similar values in each activity area in Fig. 4.8. This meant that even though the floor configuration affected sow gait, the consequent effect on floor roughness was negligible.

4.5 Conclusions

In this paper, the dynamic coefficient of friction (DCOF) and roughness of two concrete slatted floors in sow gestation rooms were tested for 21 weeks covering two gestation cycles. The floor DCOF decreased sharply (about 54%) in the first two weeks of use. This sharp decrease in floor friction was presumably due to accumulation of manure in the concrete pores. Based on this hypothesis, a friction model of two serrated surfaces was proposed to illustrate the effect of manure accumulation on floor friction. The proposed model adequately explained that the sharp decrease in DCOF was due to reduction of interlocking between the asperities of the animal foot and the concrete surface when the concrete pores were filled with manure. No significant differences in DCOF and floor roughness were observed among different areas of animal activities (dunging, high traffic, low traffic and sleeping) in the rooms, nor between two floor configurations (105-mm slats and 19-mm gaps versus 125-mm slats and 25-mm gaps). On average, the floor roughness decreased by about 36% during the test period, primarily due to accumulation of manure in the concrete pores.

5. A 2D Stick Model for Simulation of Sow walking on Concrete Floors and Detection of Sow Lameness

5.1 Abstract

A 2D stick model was developed to simulate sow walking on concrete floors. The model consisted of thirteen connective body joints to form a simple stick figure that approximates a sow's body skeleton. The video images of sows with reflective markers on their bodies walking along a corridor of concrete floor were analyzed and translated into a 2D coordinate dataset. The motion of each landmark, including displacement, velocity and acceleration were calculated. A step of walking was modelled as three consecutive phases of motion: acceleration of foot leaving the ground; constant speed of foot swinging; and deceleration of foot touching the ground. One gait cycle was separated into several time steps and the movements of each joint at a time step in x- and y-directions were described by a combination of first and 2nd order polynomial functions. The coordinates of all joints were calculated in the x (forward) and y (upward and downward) directions and these joints were then linked by synchronizing the motions of each joint at a given time step. These joint coordinates at each time step were then used to calculate a selected set of characteristic gait parameters, including the stride length and stance time for fore- and hindlimbs, diagonality, back angle and walking speed. Based on the comparisons of the predicted gait parameters between the lame and non-lame sows, the criteria were established for using the predicted gait parameters to detect sow lameness. The results showed an accuracy greater than 92% for lameness detection.

Keywords: Stick model, Sow gait, Concrete floor, Lameness detection

5.2 Introduction

Lameness has been one of the biggest concerns in the swine industry for animal welfare and productivity. Several factors can cause lameness in pigs, such as genetic musculoskeletal weakness (Jensen et al., 2009), injuries, infections (Hill, 1992; Gjein & Larssen, 1995b) and lack of exercise (Jørgensen, 2003). Locomotion visual scoring is a common method to assess the pig gait by scoring them on a scale from normal to severe lameness (Conte et al., 2014; Main et al., 2000). However, the scoring method is subjective and could be difficult to identify mild lameness (Pluym et al., 2011). Therefore, there is a need to develop objective and accurate methods to detect the lameness.

Different approaches have been explored to analyze pig gait and detect lameness. Researchers (Conte et al., 2014; Pluym et al., 2013b; Thorup et al., 2007) have used force plates to measure the asymmetry of weight distribution of each leg for detecting lameness; and some (Conte et al., 2014; Ringgenberg et al., 2010) have used accelerometers to measure the standing time, stepping behaviour and lying time for lameness detection.

Kinematics combined with computer vision was developed as a quantitative method during the last decade by considering the displacement, sequence, and time of movement without considering the forces (Clayton & Schamhardt, 2001). An effective technique is video-based analysis by digitizing movements of markers on the animal skin at specific anatomical landmarks in two or three-dimensions. Mohling et al. (2014) evaluated lameness of sows using a kinematics tool (GAITFour gait analysis walkway system) based on the stride time, stride length, maximum pressure and stance time. The lame sows showed increased stride time, decreased stride length, increased stance time and decreased maximum pressure on the lame hoof compared with the sound ones. Stavrakakis et al. (2014a) collected 3D movement data of reflective skin markers attached to leg anatomical landmarks while clinically sound and unsound pigs walked on solid concrete walkway. Their results showed that unsound pigs altered the gait in terms of joint flexion changes and asymmetry.

Most studies of lameness detection in pigs only examined the abnormalities of gait without looking at inter-limb coordination. Stick (segmental) models have been used to study the inter-limb coordination of animals and humans. Biomechanics of human walking is well understood, and simulations have been widely used to study gait and postures (Zajac et al., 2003a & 2003b). Ren et al. (2007) developed a seven-segment model to predict human walking, in which all segmental motions and ground reactions were predicted from only three simple gait descriptors (inputs): walking velocity, cycle period, and double stance duration. Chan et al. (2016) developed a 2D stick model to resemble a three-segment body structure system to model simple human body motions. Their motion estimation model applied the concept of polynomial fitting to the coordinate data. Based on comparisons to the actual motion phases in terms of classification efficiency, they confirmed the feasibility of using a 2D stick-model for human motion classification analysis. Fischer and Blickhan (2006) reviewed the kinematics of the tri-segmented therian limb from mouse to elephant to explore the general principles of the therian limb configurations and locomotions. They also investigated how the tri-segmented leg affected the design of the musculoskeletal system and the operation of legs during locomotion. Catavitello et al. (2015) used a stick model to represent the segments and markers of dogs to study the kinematic coordination of different gaits (walk, trot, gallop, and swim) of dogs. Polet and Bertram (2019) presented a simple quadrupedal model to investigate four-beat walking, two-beat running, and pseudo-elastic actuation as energetically optimum. The inelastic, planar model consisted of two-point masses connected with a rigid trunk on massless legs. Using input parameters based on measurements for dogs, their model predicted the correct phase offset in walking and a realistic walk-trot transition speed. The model could also spontaneously predict the double-hump ground reaction force in walking, and the smooth single-hump profile in trotting.

Many studies have explored the use of stick models for gait simulations, but few could be found for sows, in particular the use of gait simulations for detection of sow lameness. The aims of this paper were: (1) to develop a 2D stick model to simulate sow walking; and (2) to validate the stick model to detect lameness of sows.

5.3 Material and methods

5.3.1 2D stick model of walk

In the first phase of this project reported by Devillers et al. (2019), an experiment was conducted to study the sow gait while walking on slatted concrete floors. In the experiment, non-lame and lame sows were video recorded while walking along a corridor and nine reflective markers were placed on standardized spots of the sow's body: three on each leg from one side and three on the back (Fig. 5.1). Using the recorded video images of these reflective marks, a 2-dimensional stick model was developed in the current study to simulate the movements of a sow body during walking (Fig. 5.2).

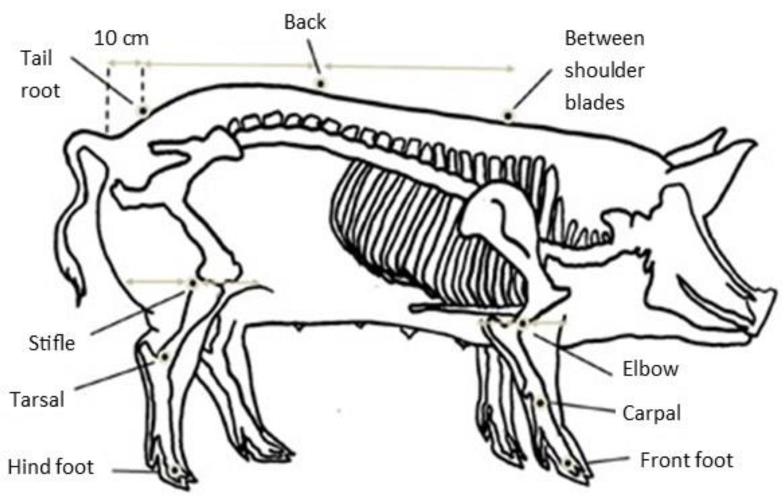


Figure 5. 1. Position of the nine reflective markers on the sow (three on each leg and three on the back) (Devillers et al., 2019)

Synovial joints in the animal body allow the body to perform various movements with inter-limb and inter-segmental coordination. The coordinated movements of joints may be simulated mechanically by inter-connected linkages. Rigid links (sticks) connected by multiple joints (stick models) have been used to study human body motions (Xiao et al., 2008; Canton-Ferrer et al., 2011; Shen et al., 2011) and some quadrupeds, like cats (Lacquaniti et al., 1999) and dogs (Catavitello et al., 2015). To simplify the mathematics in simulating the movements of walk for sows, two initial assumptions were made: (1) the gait of left and right side was the same (symmetrical), and (2) the motion of each link was coplanar (two dimensional, or 2D). Many quadrupeds, including pigs, walk in a symmetrical manner (von Wachenfelt et al., 2008). The left and right side of the body perform the same motion half a stride out of phase in a symmetrical (non-lame) gait (Abdul Jabbar et al., 2017; Remy et al., 2009).

To extract the motion data from the video images recorded in the previous phase of this project (Devillers et al., 2019), a sow skeleton was represented by its trunk and four limbs. The trunk had three landmarks on the back (joints 11, 12 and 13 in Fig. 5.2) that were used to estimate the back angle and walking speed. The forelimb consisted of the foot (joints 6 and 10), metacarpus (links 6-7 and 9-10), and radius-ulna (links 7-8 and 8-9); and the hindlimb consisted of the hindfoot (joints 1 and 5), metatarsus (links 1-2 and 4-5) and tibia (links 2-3 and 3-4) (Fig. 5.2). A gait cycle for each limb was defined as the time interval between two successive foot lifts, as indicated by the movement of joints 1, 5, 6 and 10. The flexion and extension of limbs were described by the position of three synovial joints of the respective limb, such as joints 1, 2 and 3 for one hindlimb. It should be noted that the humerus and femur segments were not specified represented in the model due to visual inaccessibility. Furthermore, the corresponding anatomical landmarks for shoulders and hips are large and lie deep within fat and muscles, which can cause great variability in kinematics study with skin markers (Clayton & Schamhardt, 2001; Stavrakakis et al., 2014b). In addition, the stifle and elbow joints of contralateral limbs were simplified as the same joint for hindlimbs (joint 3) and forelimbs (joint 8), respectively. Analysis of recorded videos showed that the stifle and elbow joints moved at a constant speed in the x-axis (horizontal) direction and moved little (< 3 cm) in the y-axis (vertical) direction. This meant the stifle and elbow joints of contralateral limbs only had a small y-axis difference in the sagittal plane. Furthermore, no angular movement was calculated in the model. Therefore, the joint 3 and joint 8 could represent the stifle and elbow joints for both left and right hindlimbs and forelimbs, respectively. It was further assumed the movement patterns of legs on both sides were the same, i.e., the equations for describing the motions of joints 2 and 4 would have the same format, but different in time sequencing, and the same was assumed for joints 1 and 5; 7 and 9; and 6 and 10.

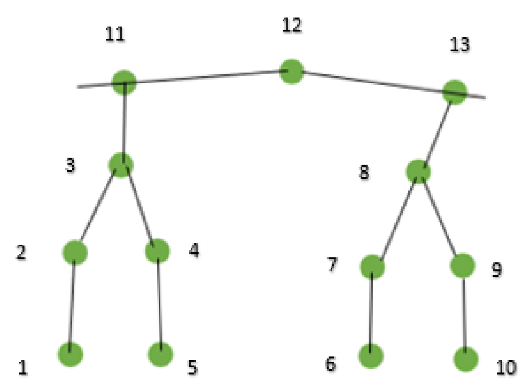


Figure 5. 2. A 2D stick model of sow body with 13 joints and 12 sticks (rigid links between joints)

Each step of walk was modelled as four consecutive movements: a foot leaving the ground, swinging, touching the ground, and stance. Each swing movement was further separated to three phases: acceleration, constant speed and deceleration. Based on the movement characteristics, one gait cycle was separated to several time steps. A step began with four feet in contact with the ground, and then one limb lifted off the ground and other joints began to move in a coordinated fashion as defined by a set of equations which predicted the coordinates (locations) of all joints (1-13) as time functions:

$$\begin{cases} x = x_0 + f(t) \\ y = y_0 + g(t) \end{cases} \tag{5.1}$$

where, x and y are the x- and y- coordinates of a joint, respectively; x_0 and y_0 are the initial coordinates defining the start location of the joints at each step; $f(t)$ and $g(t)$ represent the displacement in x and y direction, respectively, as a function of time.

In a simulation, the coordinates of all 13 joints were calculated in the x- (forward) and y- (upward and downward) directions and these joints were then linked by synchronizing the motions of each joint at a given time step. It should be noted that footfalls of quadrupedal walking are unevenly spaced in time (i.e. not 25% limb phase) (Griffin et al., 2004; Hildebrand, 1968). During walking there is at least one foot in contact with the ground throughout the gait cycle. The model was subject to the constraints: y=0 for a stance foot and y>0 for a swing foot.

5.3.2 Video data analysis

The recorded videos were used to extract coordinate data of joint movements for developing kinematics equations in the stick model (see Devillers et al., 2019 for details of video recordings). A total of twenty-four Yorkshire × Landrace sows and gilts were recorded while walking along a corridor of 6 m long, including 12 sound gilts of parity 0 or 1 with average body weight of 172 kg, and 12 lame primiparous or multiparous sows with average weight of 229 kg. The data were grouped in three sets: (1) model development, including 81 videos of non-lame sows; (2) model validation, including 15 videos of non-lame sows; and (3) model evaluation for lameness detection, including 40 videos of lame sows. Still images were first extracted from the recorded videos at time steps of 33.3 ms using GIMP (Version 2.10.10, the GIMP Development Team). The resolution of the extracted images was 744×480 pixels. The x- and y-coordinates of each reflective marker in the images were determined in the pixel scale using MATLAB

(Version 7.1.0.183 (R14), the MathWorks, Inc., Natick, MA, USA). The coordinates were then converted from pixels to meters (m) based on the calibration markers with a known dimension in the image, following a calibration procedure proposed by Clayton and Schamhardt (2001). The coordinate data of the left and right limbs obtained from the videos were pooled together because the two sides were considered to have similar locomotion characteristics (symmetrical gait). Once the x- and y-coordinates were extracted from the images, they were plotted against time to quantify the movements of each marker as functions of time, and then assess the inter-segmental coordination.

5.3.2.1 Forward movement

Figure 5.3 shows a typical pattern of measured movements of a sow foot in the x- direction during walking. From the slope of the displacement-time curve, it could be seen that first phase of walk (before swing) was acceleration of foot movement (increasing slope); the second phase was a constant speed movement (constant slope); and the third phase was deceleration (decreasing slop). A phase of movement could be mathematically described by a 2nd order polynomial for constant acceleration and deceleration or a linear function for constant speed to fit the data. The acceleration and deceleration values were then determined by differentiating the 2nd order polynomial function twice with respect to time. The constant speed was determined by differentiating the linear function once. Combining three phases of movement, the horizontal (forward) displacement of one gait cycle (the stride length) shown in Fig. 5.3 was modelled as follows:

$$D_x = \left(\frac{1}{2}a_{1x}{t_{1x}}^2\right) + (\bar{v}_x t_{cx}) + \left(\frac{1}{2}a_{2x}{t_{2x}}^2\right) \tag{5.2}$$

where,

D_x = forward travel distance of foot;

t_{1x} = acceleration time when lifting foot to walk (x represents the x-direction);

t_{cx} = time of the constant speed phase;

t_{2x} = deceleration time;

a_{1x} = acceleration at the starting of a step;

a_{2x} = deceleration (absolute value) at the end of a step;

$\bar{v}_x$ = constant speed when the foot is swinging.

The curve fitting using Microsoft Excel (Microsoft 365, Microsoft Corporation, Redmond, WA, USA) was performed to determine the coefficients in the equation.

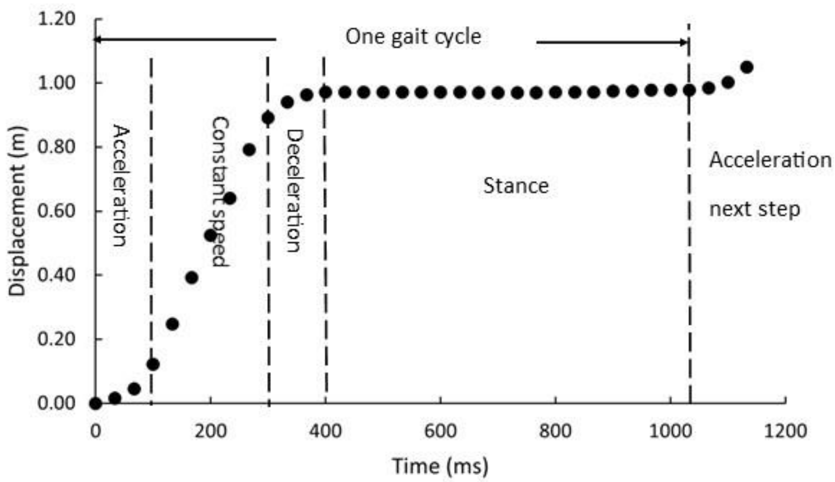


Figure 5. 3. A typical measured x- axis displacement of marker on sow foot in one gait cycle (three phases: acceleration, constant speed movement and deceleration)

5.3.2.2 Vertical movement

The displacements in the y-direction were generally small compared to the x-direction, i.e., the reflective markers moved a relatively short distance, which could lead to the markers temporarily being obscured, causing errors (Clayton and Schamhardt, 2001). Therefore, a moving-average digital filter was applied using MATLAB to smooth the y-coordinates data. The movement in the y-direction as a function of time showed a different pattern (Fig. 5.4) from the x-direction (Fig. 5.3). Based on the displacement-time plot, sow foot movements in the y-direction could be modelled in four phases: acceleration, constant speed upward, constant speed downward and deceleration.

$$D_y = \frac{1}{2}a_{1y}{t_{1y}}^2 + \bar{v}_{uy}t_{uy} + \bar{v}_{dy}t_{dy} + \frac{1}{2}a_{2y}{t_{2y}}^2 \qquad (5.3)$$

where,

D_y = vertical travel distance of foot (equals to zero when a gait cycle ends);

t_{1y} = acceleration time;

t_{uy} = time in the upward constant speed phase;

t_{dy} = downward constant speed time;

t_{2y} = deceleration time;

a_{1y} = acceleration at the starting of a step;

a_{2y} = downward deceleration (negative value) at the end of a step;

$\bar{v}_{uy}$ = upward constant speed when the foot is swinging;

$\bar{v}_{dy}$ = downward constant speed (negative value).

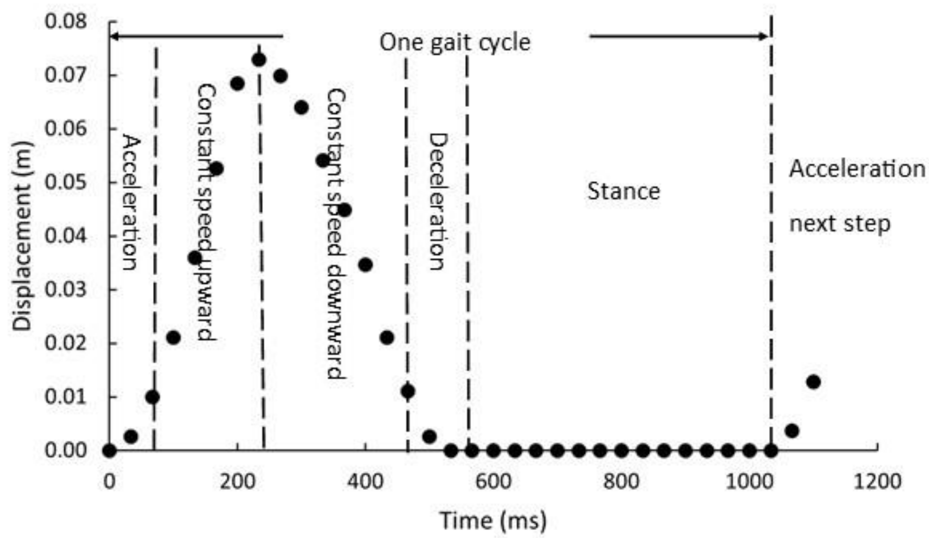


Figure 5. 4. A typical measured y- axis displacement of marker on sow foot in one gait cycle (four phases: acceleration, constant speed upward and downward movement, and deceleration)

5.3.2.3 Common equation

Based on the equations 5.2 and 5.3 for horizontal and vertical movements, a common equation was proposed for simulating the movements in both directions for one gait cycle.

$$D = \sum_i \frac{1}{2} a_a {t_a}^2 + \sum_j \bar{v} t_c \times + \sum_k \frac{1}{2} a_d {t_d}^2 \tag{5.4}$$

where,

D = displacement of joint while walking;

a_a = acceleration;

t_a = acceleration time;

$\bar{v}$ = constant speed, including upward and downward (negative value) for y-direction;

t_c = constant speed time;

a_d = deceleration (negative value for y-direction);

t_d = deceleration time;

i, j and k = how many times the joints have acceleration, constant speed and deceleration movements, respectively.

The proposed common equation could be used for any joint to model both horizontal and vertical movements with each movement divided into four phases: acceleration (AC), constant speed upward movement (CSU), constant speed downward movement (CSD) and deceleration (DC). It should be noted that some movements might not have all four phases and Table 5.1 summarizes the occurrences of each of the four phases in x- and y-directions for all joints in the model.

Table 5. 1. The times of each phase movement for markers on sow limbs in x- and y- direction during one gait cycle

	Marker position	AC	DC	CSU	CSD
x-direction	Fore foot (joint 6 and 10)	1	1	1	0
	Hind foot (joint 1 and 4)	1	1	1	0
	Carpal (joint 7 and 9)	1	1	2	0
	Tarsal (joint 2 and 4)	1	1	2	0
	Elbow (joint 8)	0	0	1	0
	Stifle (joint 3)	0	0	1	0
	Between shoulder blades (joint 13)	0	0	1	0
	Back (joint 12)	0	0	1	0
	Near tail root (joint 11)	0	0	1	0
y-direction	Fore foot (joint 6 and 10)	1	1	1	1
	Hind foot (joint 1 and 4)	1	1	1	1
	Carpal (joint 7 and 9)	1	1	2	2
	Tarsal (joint 2 and 4)	1	0	1	1
	Elbow (joint 8)	1	2	0	0
	Stifle (joint 3)	1	2	0	0
	Between shoulder blades (joint 13)	1	1	0	0
	Back (joint 12)	1	1	0	0
	Near tail root (joint 11)	1	1	0	0

Note: AC= acceleration; DC= deceleration; CSU= constant speed upward; CSD= constant speed downward; the constant speed in x-direction (forward) is represented by CSU.

5.3.2.4 Diagonality

The diagonality of gait is commonly used to describe the inter-limb coordination. It is defined as the percentage of stride time in which the footfall of the front foot follows that of a hind foot on the same side of the body (Hildebrand, 1965; Cartmill et al., 2002) (equation 5.5).

$$Diagonality = \frac{t_h - t_f}{T} \times 100\% \qquad (5.5)$$

where,

t_h = time of the footfall of the hind foot;

t_f = time of the ipsilateral footfall of the front foot;

T = stride time.

When diagonality is between 0 and 50%, the gait is called a lateral-sequence walk, which means that each hind footfall is followed by the ipsilateral fore footfall, i.e., hind left, fore left, hind right, fore right. When diagonality is between 50% and 100%, the gait is called a diagonal-sequence walk, which means that each hind footfall is followed by the contralateral fore footfall, i.e., hind left, fore right, hind right, fore left.

5.3.2.5 Trunk movement

Unlike the movement of synovial joints, the pattern of trunk movement is more difficult to quantify. The movement of trunk is caused by the skeletal system and muscular tissues connected with four limbs. It was observed that the trunk moved at the walking speed of sow in x-direction, while the movement pattern in y-direction followed a series of parabolas (Fig. 5.5). Based on the video data, the initial movement of the marker attached between shoulder blades and near tail root matched the liftoff timing of contralateral forelimbs or hindlimbs, which was possibly due to the muscle activation caused by the central nervous system (Ivanenko et al., 2006). The parabolic motion corresponded to the sequential left and right limb movement. However, the parabolic motions were continuous even when there was a short time difference between the liftoff of the contralateral limbs. For example, in Fig. 5.5 there was a time gap after HL touched down and before HR liftoff, but the marker near the tail root continued to move during this period. Therefore, the timing of parabolic movements of markers at two ends of the trunk (joint 11 and 13) were defined from the liftoff of one limb to the liftoff of the corresponding contralateral limb. For the marker attached on the back, it was observed that its movement started nearly at about the middle of the time gap between liftoff of the ipsilateral limbs. The coordinates of three joints on the trunk were also obtained based on equation 5.4, from which the back angle was calculated as follows,

$$\theta = \tan^{-1}\left|\frac{x_b - x_t}{y_b - y_t}\right| + \tan^{-1}\left|\frac{x_b - x_s}{y_b - y_s}\right| \tag{5.6}$$

where,

θ = back angle;

x_s, y_s = x- and y- coordinates of marker between shoulder blades (joint 13);

x_b, y_b = x- and y- coordinates of marker on back (joint 12);

x_t , y_t = x- and y- coordinates of marker near tail root (joint 11).

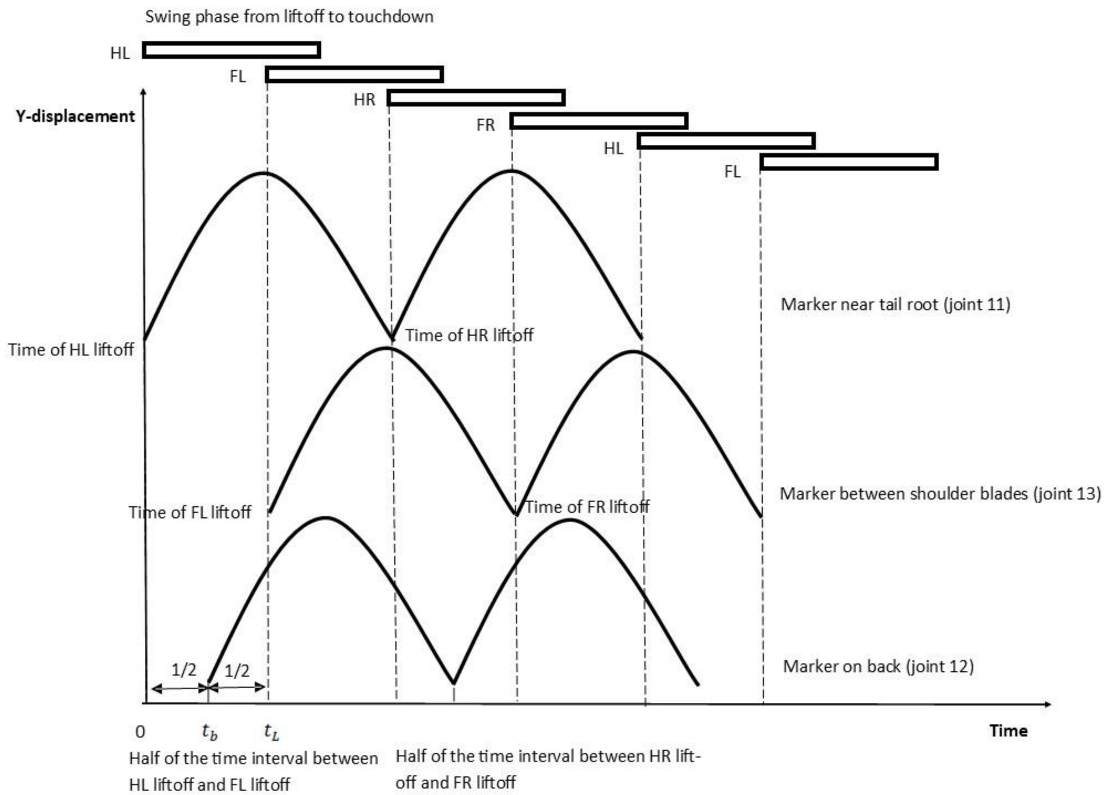


Figure 5. 5. Schematic diagram of vertical trunk movement timing corresponding to the limb movement (HL: hind left; FL: fore left; HR: hind right; FR: fore right; bar represents the swing phase of the limb from liftoff to touchdown; $\boldsymbol{t_L}$: start timing of parabolic movement of FL; $\boldsymbol{t_b}$: start timing of parabolic movement of joint 13 from the liftoff of HL; $\boldsymbol{t_b}$ equals to half of $\boldsymbol{t_L}$)

5.3.3 Statistical analysis

For each sow, the model parameters and general gait characteristics were calculated for each step and averaged for 3-4 steps. The statistical analyses were carried out with the software package SAS (Version 9.3; SAS Inst. Inc., Cary, NC). Descriptive statistics including the mean, standard deviation and standard error were calculated, and paired t-tests were performed to compare data between the predicted and the measured values. Reported results were considered statistically significant for $p<0.05$.

5.3.4 Model simulation

Each video image generated a set of model parameters, resulting in a total of 96 sets of data for non-lame sows and 40 sets for lame sows. Of the 96 sets of data for non-lame sows, 15 were randomly selected for model validation, and the remaining 81 sets were compiled as a database for model simulations for non-lame sows. A similar database of 40 sets of data was compiled for lame sows with 15 for model validation and 25 for lameness detection. To run a simulation, the value of each model parameter (acceleration/deceleration, constant speed, and their corresponding time) was randomly selected from the corresponding database for non-lame and lame sows, respectively. Other input information required in simulation included the initial coordinates of each joint related to the size of the sow, which was obtained from an image of a standing sow. Based on the coordinates measured from the image, the initial coordinates of joints were defined by keeping the same distances between joints with constraints: $y=0$ for sow feet (joint 1, 5, 6 and 10); $x=0$ for tarsal (joint 2 and 4). A simulation time step of 1/30 s was used to match the sampling frequency (30 Hz) for extracting frame images from the recorded videos. One gait cycle was separated into time steps corresponding to the four phase movements of all thirteen joints in x- and y- directions. Therefore, each phase was simulated in a time step of 1/30 s within the corresponding time duration. The coordinates of each joint were predicted at each time step using equations 1 and 4 (see Appendix B), based on which the gait characteristics were predicted in terms of the walking speed (m/s), back angle (°), diagonality (%), forelimb stride length (cm), swing time (ms), stance time (ms), and hindlimb stride length (cm), swing time (ms), and stance time (ms). The walking speed was calculated from the overall walking distance divided by the walking time, which was the sum of time durations of all movements of one foot. The stride length, diagonality and back angle were calculated from equation 2, 5 and 6, respectively. The swing time was the time when the foot was moving ($y>0$), and the stance time was the time when the foot was in contact with the ground ($y=0$).

5.4 Results and discussion

5.4.1 Measurements from video data

The average values of model parameters obtained from the extracted video data are summarized in Table 5.2. In x-direction, foot, carpal and tarsal all moved in similar patterns with three phases: AC, CS and DC during swing time, and then the foot remained in contact with ground during stance time, while carpal and tarsal still kept moving at an average constant speed (CS_2, where the subscript 2 means the second CS) of 0.2 and 0.3 m/s, respectively. The elbow, stifle and trunk of sow continuously moved at a constant speed of 0.9 m/s during walking in horizontal direction. The movement pattern of each joint in the y-direction was more complicated than in the x-direction. The displacement-time plot could be presented by a series of parabolas and each parabola represented a characteristic phase of walking: AC, DC, CSU or CSD, as described in Table 5.2. As shown in Fig. 5.6, the carpal presented a movement pattern different from tarsal, consisting of five phases of movement: AC, CSD, CSU, DC and CSD_2 during swinging, with a constant CSU_2 of 0.1 m/s during stance period. The parabola of tarsal could be simply described by a CSU of 0.3 m/s and a CSD of -0.2 m/s. Between each parabola (stance time), the tarsal moved at an acceleration of 0.2 m/s^2. It should be noted that some time parameters were omitted in the table for some cases because the movement time could be defined by the time period of other joint movements. For example, the carpal of right forelimb kept moving at CS of 0.2 m/s (x-direction) during stance phase, but the stance time was not included in the model as an independent variable because it could be calculated from the movements of three limbs.

Table 5. 2. Average values and standard deviations of measured model parameters for all joints of non-lame sows (n=81)

	Parameters	Fore foot (joint 6 and 10)	Hind foot (joint 1 and 5)	Carpal (joint 7 and 9)	Tarsal (joint 2 and 4)	Elbow (joint 8)	Stifle (joint 3)	Between shoulder blades (joint 13)	Back (joint 12)	Near tail root (joint 11)
x-axis	AC (m/s^2)	13.1±6.6	13.2±6.6	13.0±5.8	5.5±3.3	n/a	n/a	n/a	n/a	n/a
	ACT (ms)	123±31	133±28	120±29	125±29	n/a	n/a	n/a	n/a	n/a
	CS (m/s)	4.0±0.2	3.7±0.2	3.0±0.2	2.9±0.2	0.9±0.04	0.9±0.04	0.9±0.04	0.9±0.04	0.9±0.04
	CST (ms)	167±27	176±26	163±27	180±26	n/a	n/a	n/a	n/a	n/a
	DC (m/s^2)	14.5±3.8	14.7±3.6	8.4±3.6	13.6±3.6	n/a	n/a	n/a	n/a	n/a
	DCT (ms)	133±30	124±26	140±32	128±29	n/a	n/a	n/a	n/a	n/a
	CS_2 (m/s)	n/a	n/a	0.2±0.03	0.3±0.02	n/a	n/a	n/a	n/a	n/a
y-axis	AC (m/s^2)	2.4±0.5	2.1±0.4	4.1±1.7	0.2±0.06	0.3±0.07	0.6±0.05	0.2±0.06	0.2±0.06	0.3±0.06
	ACT (ms)	133±28	100±18	123±27	n/a	260±38	266±36	259±36	279±38	281±37
	CSU (m/s)	0.2±0.03	0.5±0.04	0.4±0.04	0.3±0.03	n/a	n/a	n/a	n/a	n/a
	CSUT (ms)	103±20	142±32	103±18	167±28	n/a	n/a	n/a	n/a	n/a
	CSD (m/s)	-0.3±0.02	-0.7±0.04	-0.4±0.03	-0.2±0.03	n/a	n/a	n/a	n/a	n/a
	CSDT (ms)	97±16	103±21	67±5	266±37	n/a	n/a	n/a	n/a	n/a
	DC (m/s^2)	-4.7±1.9	-2.8±0.5	-18.0±4.9	n/a	-1.5±0.2	-2.0±0.4	-0.2±0.06	-0.3±0.06	-0.5±0.06
	DCT (ms)	90±22	88±22	74±16	n/a	163±27	167±26	245±38	227±35	223±33
	CSU_2 (m/s)	n/a	n/a	0.1±0.02	n/a	n/a	n/a	n/a	n/a	n/a
	CSD_2 (m/s)	n/a	n/a	-0.2±.03	n/a	n/a	n/a	n/a	n/a	n/a

$CSDT_2$ (ms)	n/a	n/a	100±20	n/a	n/a	n/a	n/a	n/a	n/a
DC_2 (m/s^2)	n/a	n/a	n/a	n/a	-0.2±0.03	-0.3±0.03	n/a	n/a	n/a

Note: AC= acceleration; ACT= acceleration time; CS= constant speed; CST= constant speed time; DC=deceleration; DCT= deceleration time; CS_2= second constant speed; CSU= upward constant speed; CSUT= upward constant speed time; CSD= downward constant speed; CSDT= downward constant speed time; CSU_2= second upward constant speed; CSD_2= second downward constant speed; $CSDT_2$= second downward constant speed time; DC_2= second deceleration; "n/a" means no respective movement.

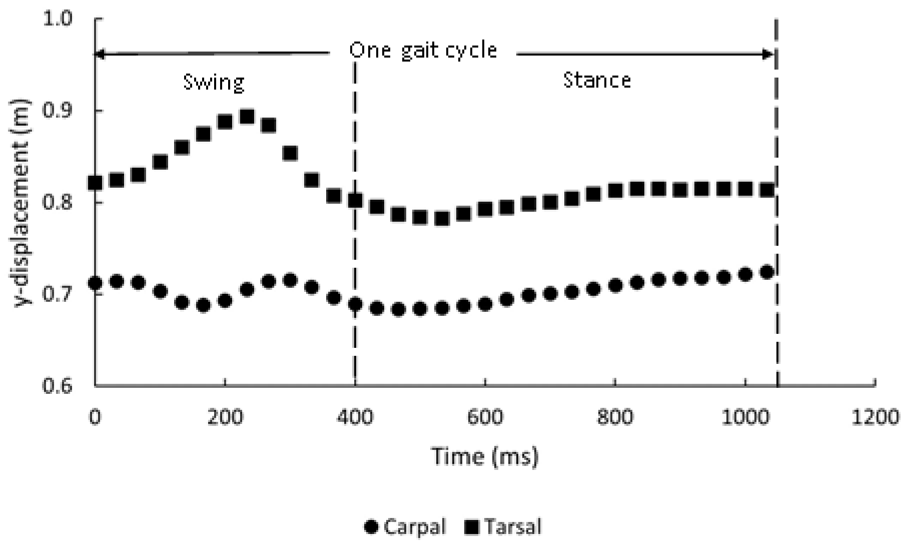


Figure 5. 6. Typical measured y-displacements of carpal and tarsal joints in one gait cycle (from liftoff to stance)

The 81 sets of model parameters listed in Table 5.2 approximately followed a normal distribution. Figure 5.7 shows a typical distribution pattern of the constant speed time for forefeet of 81 sows in x-direction. The CST of forefeet in x-direction ranged from 67 ms to 233 ms with a peak at 167 ms. Around 92% sows had CST in x-direction in 133-200 ms.

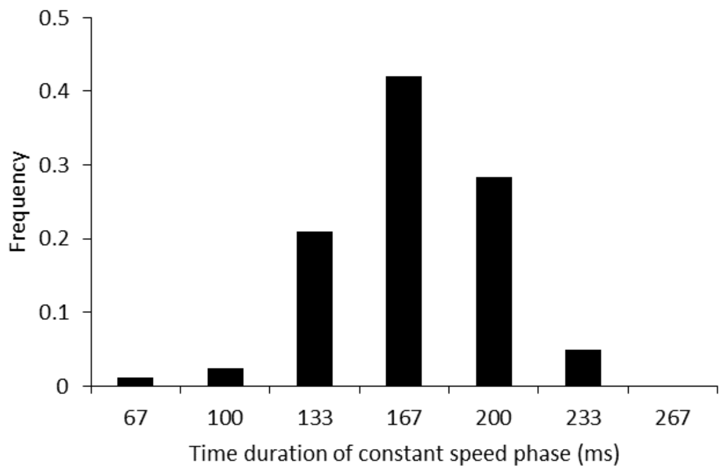


Figure 5. 7. Distribution of the time duration of the constant speed phase for sow forefoot in x-direction

The general gait characteristics represented by a set of kinematics parameters for non-lame sows are summarized in Table 5.3. All sows displayed a lateral-sequence walk (0 < diagonality < 50%), as expected for most mammals (Cartmill et al., 2002), such as dogs (Catavitello et al., 2015). The average walking speed (0.89 m/s) agreed with Thorup et al. (2007) (0.88 m/s). The back angle of 172° was also in line with the value (172°) reported by Devillers et al. (2019). The average stride lengths of forelimb and hindlimb were 89 cm and 88 cm, respectively. Conte et al. (2014) analyzed the gait of sows using kinematics and found the average stride lengths were 82 cm for forelimb and 81 cm for hindlimb. The swing time of forelimb and hindlimb were 426 ms and 433 ms, repectively. Conte et al. (2014) reported sows had average swing time of 426 ms for forelimb and 421 ms for hindlimb. However, the stance time reported by Conte et al. (2014) (523 ms for forelimb and 532 ms for hindlimb) are shorter than the values in this study (567 ms for forelimb and 570 ms for hindimb). Thorup et al. (2007), and von Wachenfelt et al. (2009) found the stance time of fore- and hindlimbs were 600 ms and 470 ms, respectively. The swing duration accounted for 43% of a gait cycle in this study, similar to Conte et al. (2014) (44% gait cycle) and Thorup et al. (2007) (40% gait cycle).

It should be noted that some gait parameters, such as stride length, are dependent on animal size (McMahon, 1975). In the simulation model of this study, the pig body size (length) was nominally represented by the total length of two rigid sticks (links 11-12 and 12-13 in Figure 5.2), which approximated the pig trunk length in the model. This size parameter was entered into the model by specifying the initial coordinates of joints 11, 12, and 13. Of the 81 non-lame sows tested, the average nominal length was 96±6 cm. The small standard deviation indicated that the tested sows covered a relatively narrow size range. A preliminary test was carried out to test if different nominal lengths had impact on the gait parameters. The results showed the same gait parameter predictions when the same model parameters in Table 5.2 and the different size parameter inputs were entered. This meant this model did not consider the size effect and only considered the joint movements. The model parameters in Table 5.2 of 81 non-lame sows were also categorized into two size categories: big (nominal length>96 cm) and small (nominal length≤ 96 cm) for comparison. The paired t-test showed that the effect of sow size on the model parameters in Table 5.2 was not significant. A possible reason why the sow size did not have an effect on the model parameters could be low sampling frequency (30 Hz), that is, only about 3 - 5 data points during short-duration movements, such as acceleration and deceleration.

Table 5. 3. Measured gait characteristics of non-lame sows (n=81)

Kinematics parameter	Mean	SD
Walking speed (m/s)	0.89	0.04
Back angle (°)	172	3
Diagonality (%)	24	3
Forelimb		
Stride length (cm)	89	4
Swing time (ms)	426	31
Stance time (ms)	567	43
Hindlimb		
Stride length (cm)	88	3
Swing time (ms)	433	34
Stance time (ms)	570	45

5.4.2 Comparisons of stick model simulations with measurements

The predicted gait characteristics were in good agreement with the measurements when compared with a dataset for 15 non-lame sows that were not used in model parameter determination, with average percentage differences (equation 5.7) between 2% to 9% (Table

5.4). The paired t-test showed there were no significant differences (P>0.05) between the predicted and measured gait characteristics.

$$Percentage\ difference = \frac{|measured - predicted|}{measured} \times 100\% \quad (5.7)$$

Figure 5.8 shows the plot of predicted versus measured gait parameter (walking speed) for the 15 non-lame sows. The data points were scattered around the ideal line (solid line with a slope of 1), which indicated the predicted value and the measured value fit well. In addition, a hypothesis test was carried out to test if the slope was significantly different from 1 (slope of the ideal line), and the null hypothesis (slope=1) was accepted (p=0.49), i.e., the regression slope was not statistically different from 1. Therefore, the model could adequately predict the sow movement.

Table 5. 4. Average values and standard errors (SE) of gait characteristics of predicted and measured results of non-lame sow and average difference between predictions and measurements (n=15)

Gait characteristics	Predicted (Mean (SE))	Measured (Mean (SE))	Average percentage difference
Walking speed (m/s)	0.89 (0.01)	0.91 (0.01)	4%
Back angle (°)	174 (1)	171 (1)	3%
Diagonality (%)	24 (1)	25 (1)	9%
Forelimb			
Stride length (cm)	90 (1)	89 (2)	6%
Swing time (ms)	429 (10)	435 (8)	10%
Stance time (ms)	589 (13)	578 (14)	8%
Hindlimb			
Stride length (cm)	89 (1)	90 (1)	4%
Swing time (ms)	433 (9)	421 (7)	6%
Stance time (ms)	580 (13)	574 (15)	8%

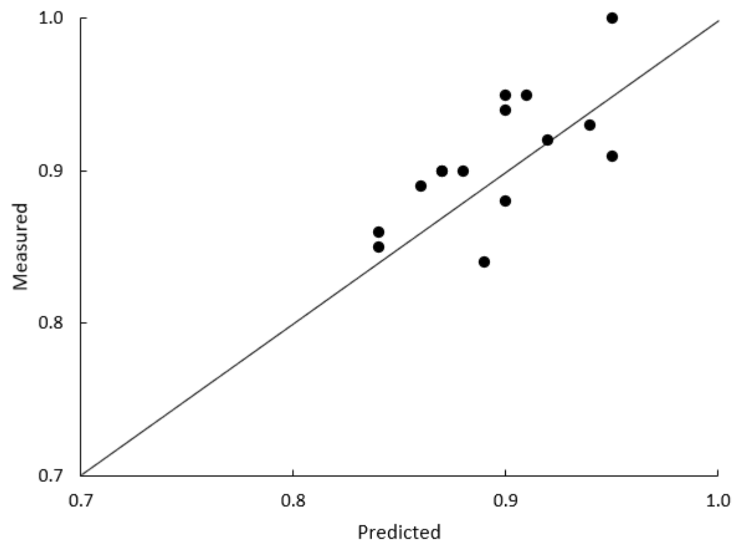


Figure 5. 8. The predicted vs measured values of walking speed of 15 non-lame sows (solid line indicates the ideal fit line with a slope of 1)

5.4.3 Detecting lameness

5.4.3.1 Selection of gait parameters for lameness detection

Lameness affects sow gait. The model developed in this study predicted the gait characteristics of non-lame sows. It was hypothesized that if the measured gait parameter(s) of a sow was deviated "significantly" from the model prediction, the sow would be lame. To use this method for detecting lameness required the answers to the following two questions: i) what gait parameter(s) should be used in determining the deviation(s) of lame sows from the non-lame sows? and ii) how much (significant) deviation(s) was sufficient to differentiate lame sows from non-lame sows? The first question involved identifying the most sensitive gait parameter(s) predicted by the model for detecting lameness and the second question required defining the threshold of the identified parameters. To answer these two questions, all gait characteristics predicted by the model were compared with the measured values for 15 lame sows assessed by visual gait scoring based on the method described by Devillers et al. (2019) (0: normal gait; 1: abnormal stride length is detected; no obvious lameness; 2: stride is shortened and lameness is detected; 3: sow does not place affected limb on the floor; 4: non-ambulatory sow) (Table 5.5). Compared to the model predictions, the lame sows had slower walking speeds and narrower back angles (Table 5.5). The lame sows still displayed a lateral-sequence walk, but with a lower diagonality (22%) than that for the non-lame sows (24%). The average stride lengths of forelimbs and hindlimbs of lame sows were shorter than the model predictions with average differences of 12% and 7%, respectively. The swing time did not show any significant difference between the model predictions and measurements for both forelimbs and hindlimbs. There were significant differences in stance time between the model predictions (587 ms for forelimb and 593 ms for hindlimb) and the measurements for lame sows (682 ms and 691 ms for fore- and hind-limb, respectively). Grégoire et al. (2013) found the lame sows tended to have a shorter stride length, a lower walking speed, a longer stance time and an arched back when compared with non-lame sows. Flower et al. (2005) explained that the lame animals reduce the walking speed and stride length and increase the stance time as an adaptation to decrease pain. In the current research, the paired t-test showed all variables except swing time were significantly different ($P<0.05$) between model predictions for non-lame sows and measured values for lame sows. The plot of predicted and measured gait parameter in Figure 5.9 also showed that the predicted walking speed of non-lame sows were statistically higher than the measured values for non-lame sows. A hypothesis test for the regression slope showed the slope was significantly different from 1.

Table 5. 5. Average values and standard errors of gait characteristics of model predictions and measurements of lame sows and average difference between predictions and measurements (n=15)

Gait characteristics	Predicted (non-lame sows)	Measured (lame sows)	Average difference	p-value
Walking speed (m/s)	0.89 (0.01)	0.80 (0.02)	10%	0.0000018
Back angle (°)	173 (1)	167 (1)	5%	0.00046
Diagonality (%)	24 (1)	22 (1)	16%	0.034
Forelimb				
Stride length (cm)	90 (1)	86 (2)	12%	0.045
Swing time (ms)	429 (7)	433 (9)	7%	0.099
Stance time (ms)	587 (11)	682 (16)	14%	0.0000038
Hindlimb				
Stride length (cm)	91 (1)	87 (2)	7%	0.043
Swing time (ms)	433 (8)	421 (8)	9%	0.14
Stance time (ms)	593 (14)	691 (15)	14%	0.0000061

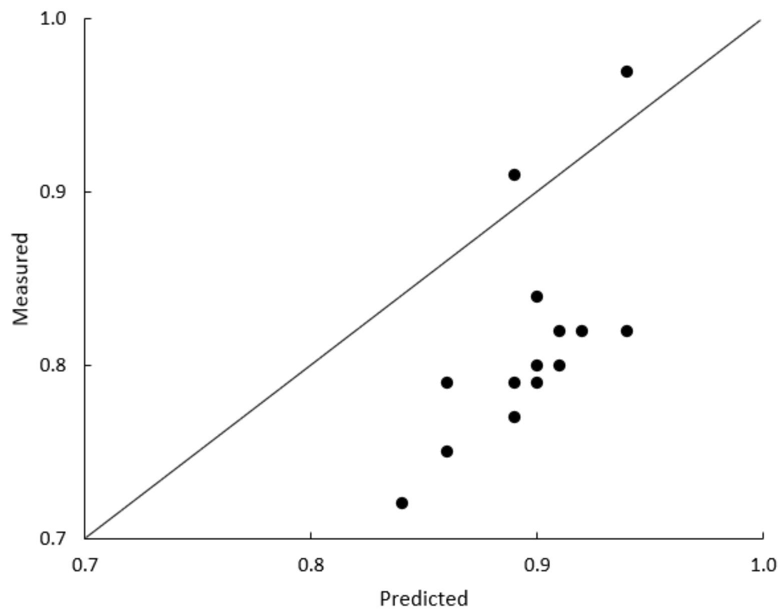


Figure 5. 9. The predicted vs measured values of walking speed of 15 lame sows (solid line indicates the ideal fit line with a slope of 1)

The above comparisons revealed that there were significant differences in gait parameters between the model predictions and the measured values for lame sows, indicating the potential of using the proposed 2D stick model to detect sow lameness. Based on the magnitudes of differences between the model predictions and the measurements shown in Table 5.5, the back angle, walking speed, diagonality, stance time and stride length for fore- and hindlimbs were selected for detecting lameness. There was a large difference in diagonality between the predicted and measured values, but no research was reported in the literature that investigated the difference between non-lame and lame pigs in terms of diagonality. The selection of the other six parameters was in line with findings reported in the literature (Conte et al., 2014; Devillers et al., 2019; Grégoire et al., 2013; Thorup et al., 2007), which have shown that the back angle, walking speed, stance time and stride length are most sensitive to lameness. The seven selected parameters formed the basis for lameness detection in the proposed model. If the differences in these seven parameters between the model predictions and measurements were not significant, the sow would be considered non-lame; otherwise, the sow would potentially be considered lame and further assessment would be conducted to confirm lameness (discussed in the following sections).

It should be noted that the lame sows in this study were larger than the non-lame sows. The average body length of 15 lame sows was 106±5 cm, and was longer than the average body length (96±6 cm) for non-lame sows used in the model development. The size of the sows might have an impact on the differences in gait characteristics between the model predictions and lame sow measurements. However, a preliminary test was conducted to investigate the effect of sow size on the model parameters in Table 5.2 for non-lame sows, and no significant difference was found. None-the-less, the small-scale data (81 sets) and low sampling frequency (30 Hz) suggest that the effect of animal size on gait characteristics should be investigated on a larger scale. Classifying different weight-level sows might help improve the accuracy of lameness detection. Moreover, a high-speed camera would be recommended due to the short duration of acceleration and deceleration movements.

5.4.3.2 Deviation thresholds of gait parameters for lameness detection

Discussion in the above section established that if a sow was lame, the measured gait parameters would deviate from the model predictions. However, the challenge was that there were natural variations in sow gait even for non-lame sows, as indicated by Table 5.4. Therefore, it was necessary to establish a deviation threshold for each selected gait parameter to detect lameness. To do so, the frequency distributions of differences between predictions and measured data for non-lame sows were first examined, and then compared with lame sows (Fig. 5.10). As expected, the differences between the model predictions and the measurements for non-lame sows were less than those for lame sows. To determine a deviation threshold for each gait parameter, four criteria parameters were adapted from Poursaberi et al. (2010):

$$Accuracy = \frac{tp+tn}{tp+tn+fp+fn}$$

$$Sensitivity = \frac{tp}{tp+fn}$$

$$Specificity = \frac{tn}{tn+fp}$$

$$Error\ rate = \frac{fp}{tp+fp} \tag{5.8}$$

where,

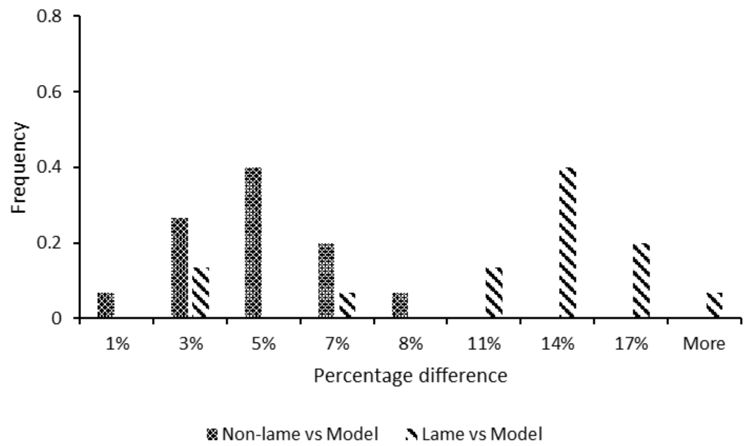
tp = true positive rate;

tn = true negative rate;

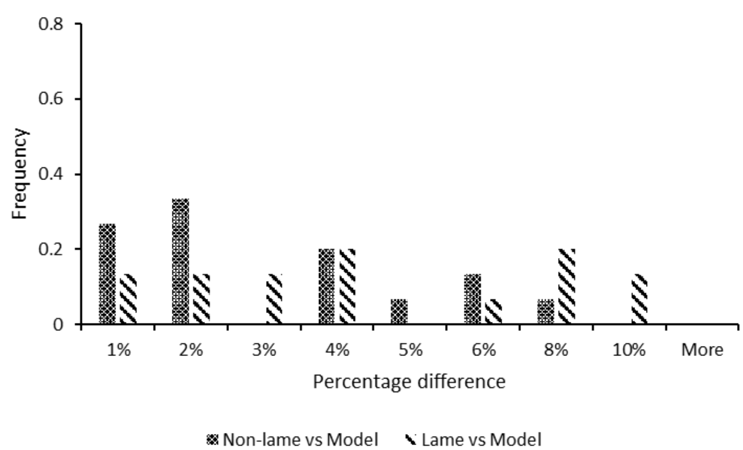
fp = false positive rate;

fn = false negative rate.

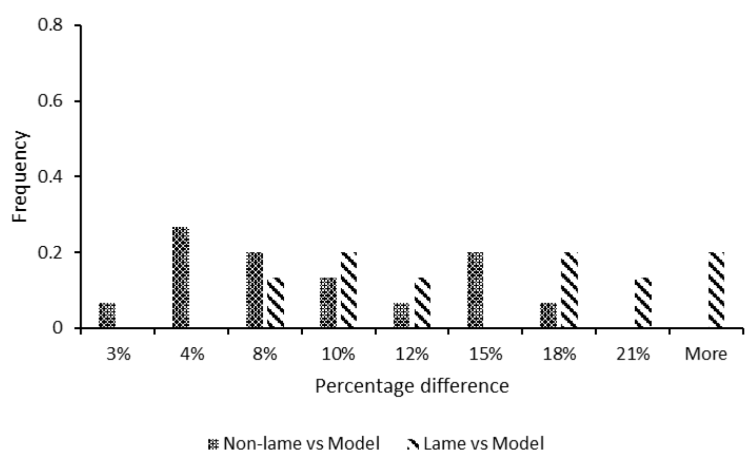
The four criteria parameters were used to quantify the adequacy of the selected deviation threshold. Taking the walking speed as an example (Fig. 5.10a), the differences between the model predictions and the measurements for non-lame sows ranged from 1% to 8% with a peak at 5%, while the corresponding differences for lame sows ranged from 3% to 17% with a peak at 14%. The above comparison indicated that 5% or 8% difference could be selected as a threshold. For 5%, the corresponding tp, tn, fp and fn values were determined from Fig. 5.10 as 0.867, 0.667, 0.333 and 0.133, respectively, and the accuracy was determined from equation 5.7 as 60%. For 8%, the tp, tn, fp and fn values were 0.800, 0.067, 0.933 and 0.200, respectively, and the corresponding accuracy was 87%. Therefore, the difference of 8% was selected as the deviation threshold for the walking speed, and the corresponding sensitivity, specificity and error rate were 80%, 93% and 8%, respectively. Since variation of the percentage of difference between the model prediction and the measurement showed an overlap between lame and non-lame sows, any threshold would lead to either problem of specificity or sensitivity. Using the deviation threshold of 8% could correctly identify 80% (sensitivity) of the lame sows and miss 20%; and correctly identify 93% (specificity) but misidentify 7% of non-lame sows as lame. An error rate of 8% meant that 8% of sows identified as being lame might be non-lame (Table 5.6). Following the same procedure, the deviation thresholds of all seven selected parameters were determined and the respective sensitivity, specificity and error rate were calculated as well (Table 5.6).



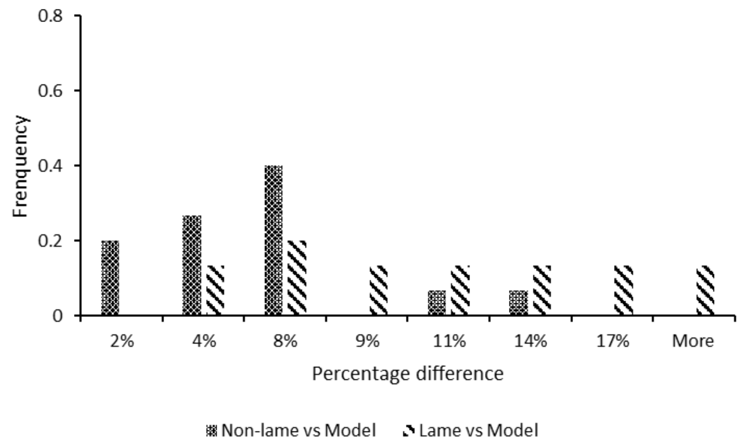
(a) walking speed



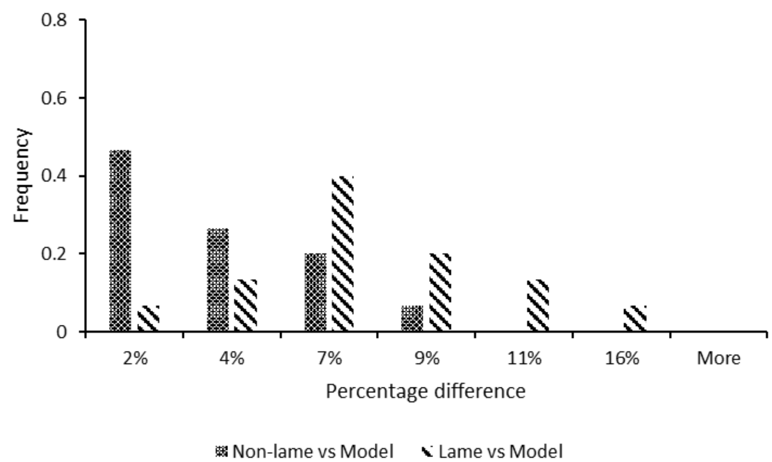
(b) back angle



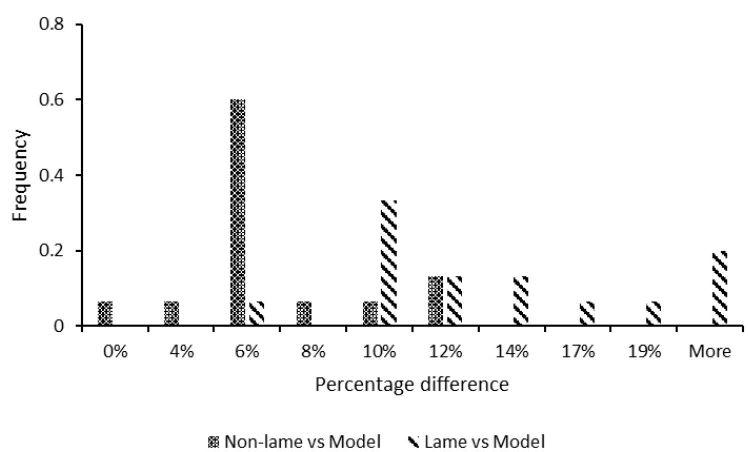
(c) diagonality



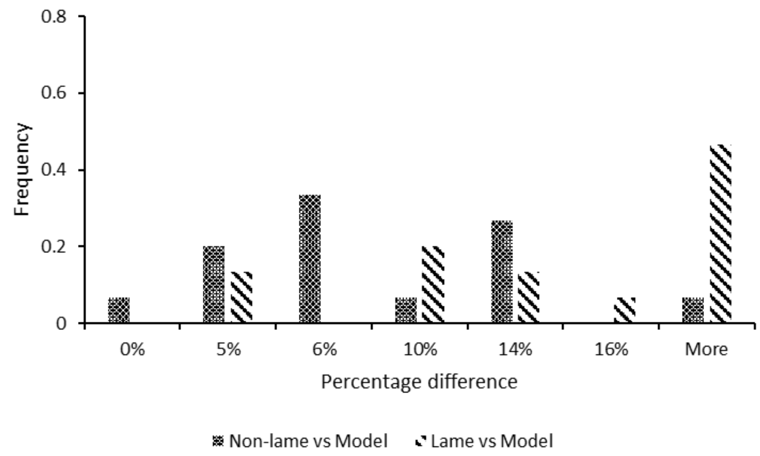
(d) stride length (forelimb)



(e) stride length (hindlimb)



(f) stance time (forelimb)



(g) stance time (hindlimb)

Figure 5. 10. Distribution of the percentage differences of gait parameters between the measured data and model predictions for non-lame and lame sows

Table 5. 6. Deviation thresholds of gait parameters

Gait parameters	Threshold	Accuracy	Sensitivity	Specificity	Error rate
Walking speed	8%	87%	80%	93%	8%
Back angle	3%	67%	73%	60%	35%
Diagonality	10%	70%	87%	53%	35%
Forelimb					
Stride length	9%	77%	67%	87%	17%
Stance time	10%	87%	93%	80%	18%
Hindlimb					
Stride length	7%	77%	80%	73%	25%
Stance time	10%	73%	87%	60%	32%

For certain parameters, if the difference between the measured value and the model prediction was over the corresponding threshold, the measured value was compared with the predicted value to see if the direction of the deviation would be physically meaningful. For example, if the deviation between the measured and predicted values for the back angle exceeded the threshold (3%), but the measured back angle was greater than the predicted value, which meant that the sow was still considered non-lame because the back was not arched.

5.4.4 Optimization and verification

To verify the proposed method of detecting sow lameness, a dataset for 25 lame sows were tested. First, a single parameter (one of the seven selected parameters) was used to detect lameness, and then the multiple parameter combination was optimized. When a single parameter was used, the accuracy ranged from 80% to 96%, with the highest accuracy when the stance time was used (Table 5.7). The underlying reason for variable accuracies of different parameter was that lameness was not necessarily the same for all sows, and the way gait was affected could vary depending on the cause of lameness, and which legs and the number of legs were affected. Therefore, combinations of multiple parameters might provide a more accurate indicator to detect lameness whatever its cause or its severity.

Table 5. 7. Lameness detection accuracy of the seven gait parameters

Gait parameters	Accuracy	Average weight
Walking speed	92%	11±15
Back angle	80%	1±2
Diagonality	84%	5±8
Forelimb		
Stride length	80%	9±17
Stance time	96%	4±3
Hindlimb		
Stride length	84%	7±11
Stance time	88%	4±4

To optimize the combination of seven selected parameters for lameness detection, a weight was assigned to each parameter to reflect its sensitivity to lameness. This weight was calculated as the difference between the deviation from the established threshold. The larger the weight, the more sensitive the parameter. For example, if a deviation of walking speed was 11% while the threshold was 8%, the weight of walking speed would be 3 (11% − 8%). If the deviation of a parameter was less than the threshold, the weight would be a negative value. The calculated average weights of the seven parameters are summarized in Table 5.7. The large standard deviations in Table 5.7 indicated big differences among lame sows in terms of the gait parameters. These weights could be used as a guide to select the optimal parameter(s) to be used to detect lameness. However, the higher weight did not necessarily result in higher accuracy (Table 5.7). For example, the highest accuracy (96%) was from the forelimb stance time which had an average weight of 4, while the accuracy for the forelimb stride length was 80% with an average weight of 9. This meant that a single parameter might not be always the best indicator of lameness. Hence, multiple parameter combinations could be used to improve the reliability of detection of lameness. The following discussion uses two-parameter combinations (21 combinations in total) to illustrate the procedure of combining multiple parameters. For two parameters with weights W_i and W_j, respectively, a weight index was calculated as follows:

$$weight\ index = \frac{W_i + W_j}{W_t} \times 100\% \tag{5.8}$$

where,

W_i, W_j = weights of any two parameters;

W_t = sum of weights of seven parameters.

The calculated indices for all 21 possible combinations are shown in Table 5.8. It can be seen that the combination of the walking speed and the forelimb stance time had the highest index (62%), followed by the combination of the walking speed and the hindlimb stance time (53%) (Table 5.8). Figure 5.11 shows the accuracy of detecting lameness using 21 combinations of gait parameters. It should be noted that the accuracy was calculated under the condition that the sow was considered as lame when both parameters in the combination had deviations greater than the threshold. All combinations showed accuracy higher than 92% and 13 out of 21 combinations had an accuracy of 100%. Using the walking speed and forelimb stance time combination (WS+STF) with the highest weight index (62%), the model showed an accuracy of 100%. The D+SLF combination with the lowest index (1%) resulted in an accuracy of 96%. The lowest accuracy (92%) occurred at the BA+SLH combinations (weight index: 17%). Even though the accuracy with the weight index did not show an increasing trend due to relatively small test dataset, the two-parameter combinations improved the reliability and the accuracy of lameness detection (Table 5.7). According to the high accuracy and high weight index, the WS+STF combination was considered as the optimal model indicator to detect lameness.

Table 5. 8. Summary of combined weight index for two parameters

Combinations	Back angle	Diagonality	Stride length (forelimb)	Stance time (forelimb)	Stride length (hindlimb)	Stance time (hindlimb)
Walking speed	36%	49%	17%	**62%**	46%	**53%**
Back angle		20%	12%	33%	17%	24%
Diagonality			8%	46%	30%	37%
Stride length (forelimb)				14%	2%	5%
Stance time (forelimb)					43%	50%
Stride length (hindlimb)						34%

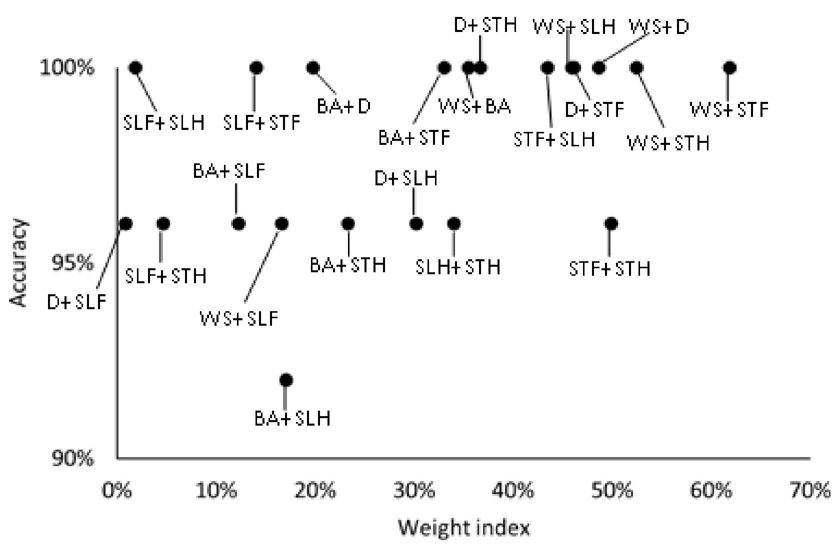


Figure 5. 11. Accuracy of lameness detection using different two-parameter combinations (WS: walking speed; BA: back angle; D: diagonality; SLF: stride length – forelimb; STF: stance time – forelimb; SLH: stride length – hindlimb; STH: stance time - hindlimb)

The model could detect the sow lameness with an accuracy up to 100%, which is close to the model of Poursaberi et al. (2010) for dairy cattle. They developed an automatic system for lameness assessment with an accuracy of 96% by analyzing the back curvature based on 2D side view images. Pluym et al. (2013b) developed a detection system, SowSIS (sow stance information system) based on force stance variables from force plate analysis and visual stance variables from images. The preliminary results showed the potential of SowSIS to detect sow lameness. Briene et al. (2019) then built SowSIS into an electronic sow feeder for lameness detection and obtained 76.7% lame predictive value and 87.0% non-lame predictive value. Zhu & Zhang (2010) built a stick model of pig limbs to detect pig lameness by assessing the swing angle of carpal and tarsal joints and the model showed an accuracy of 90%.

Even though the present model showed an accuracy greater than 92%, some limits of the model should be noted. The model was developed on relatively small size datasets and only tested on lame sows (positive subjects). Since some gait parameters are dependent on sow size, such as stride length, large datasets covering a range of sow sizes should be used to expand the database of the model parameters and test the model for its sensitivity to sow size. The model should be tested on large datasets of non-lame (negative) and lame (positive) sows in the future.

5.5 Conclusions

In this research, a 2D stick model was developed to simulate sow walking and detect sow lameness. A sow was represented by 13 joints connected by 12 sticks in the stick model. Movements of each joint could be modelled by a combinations of 2^{nd} order polynomial functions and linear functions. The model parameters were determined from the data extracted from recorded video images of sow walking. The simulated movement coordinates of all 13 joints during walking could be used to predict a selected set of gait parameters. It was found that the stick model adequately predicted the gait parameters, including the stride length and stance time for fore- and hindlimbs, diagonality, back angle and walking speed. The stick model could be used to detect lameness of sows, with an accuracy greater than 92% for lameness detection. Although the 2D stick model developed in this research was primitive, it did show a promising ability to detect sow lameness. More validation with a larger-scale of datasets could be done to enhance the robustness of the model.

6. Overall Summary and Conclusions

6.1 Overall Summary and Discussion

Flooring in pig barns plays an important role in animal health and welfare. In this thesis, two significant issues of concrete flooring in gestation sow barns were addressed: (i) configurations and properties of slatted concrete floors as related to manure drainage and slipperiness, and (ii) gait of sows on slatted concrete floors as related to lameness. In a previouse study, Devillers et al. (2019) reported that a configuration of slatted concrete floor with 105-mm slats and 19-mm gaps (105/19 configuration) was optimal for gestating sows in terms of affecting sow's gait. In the first part of the current study, this optimal floor configuration was evaluated for manure drainage and compared with the commonly used configuration of 125 mm slats and 25 mm gaps (125/25 configuration). An experiment was conducted to measure floor cleanliness and animal cleanliness in two sow gestation rooms, as well as the indoor ammonia concentration which is closely related to manure accumulation on the floors. By comparing the in-barn air quality and cleanliness of floor and animals between two slatted concrete floors (105/19 vs. 125/25), it was concluded that the narrow slat and gap floor (105/19) was as effective for manure drainage as the commonly used floor of 125 mm slat and 25 mm gap (125/25). This meant the narrow slat and gap floors could be used in gestation barns to improve sow comfort and leg health without negative impact on manure drainage and in-barn air quality. One limitation of this study was that even though the stock density in the tested room was 2.2 m^2/sow within the range provided by the Canadian Code of Practice for pigs (National Farm Animal Care Council, 2014) (1.4 to 2.2 m^2/sow), but only one of two pens in each room (50% of room) was used. In other words, there was more space for ammonia to dilute in the room, resulting in low ammonia concentrations, compared with a fully stocked room.

Much research (Sommers et al., 2003; Heinonen et al., 2006; Kilbride et al., 2009b; Cador et al., 2014) has shown that claw injuries of animals are closely related to slipperiness and abrasiveness of concrete floors, which are associated with the surface friction and roughness of concrete floors. The feet lesions and lameness could be caused by rough surfaces of concrete floor due to abrasion or by slipperiness of floor (Gjein & Larssen, 1995b). On the other hand, pig activities and manure presence on the floor in the barn could change the surface properties of the concrete floors (Phillips & Morris, 2000). No studies have addressed the issues of surface properties of concrete floors while occupied by sows in barns. In the second part of this thesis research, an experiment was conducted to assess the in-situ surface properties of slatted concrete floors and the relationships between surface properties and duration of use and between surface properties and different animal activity areas in the pen were investigated. The surface friction and roughness of newly installed concrete floors occupied by sows in gestation rooms were measured during two gestation cycles. A significant finding in this study was that the dynamic coefficient of friction (DCOF) decreased sharply (about 54%) in the first two weeks of use of new concrete floors due to accumulation of manure in the concrete pores. On average, the floor roughness decreased by about 36% during the test period, primarily due to accumulation of manure in the concrete pores. No significant differences in DCOF and floor roughness were observed among different areas of animal activities (dunging, high traffic, low traffic and sleeping) in the rooms, nor between two floor configurations (105-mm slats and 19-mm gaps versus 125-mm slats and 25-mm gaps). This meant that the floor configuration (slat and gap widths) might affect sow gait, but not floor friction and roughness. In addition, the sleeping area had around 15% manure coverage and the dunging area had about 50% manure coverage after the first week of use, but no significant differences in DCOF were found between different floor areas. A reason for this observation was that the floor was scraped before friction test which eliminated the direct effect of manure on surface friction (i.e., there was no layer of manure between the simulated foot and the concrete surface), while the amount of manure accumulated in the pores was very small and limited by the pore depths (more manure on the surface would not result in more manure in the pores after a certain point).

A missing link in many studies of concrete floors in animal facilities is the animal behavior as related to floor properties, such as sow gait while walking on concrete floors. In the third part of this thesis research, a two-dimensional stick model was developed to simulate sow walking on slatted concrete floors and predict a set of gait parameters. The 2D stick model was composed of 13 joints connected by 12 (rigid) sticks that approximated a sow's body skeleton. A unique feature of stick models is the inter-limb coordination during sow walking. The motions of each joint were mathematically described by a set of polynomials with coefficients determined from the video data of sows walking along a corridor of concrete floor. Based on the simulated movements of all 13 joints, a set of gait parameters were predicted, including the stance time and stride length for fore- and hind limbs, back angle, walking speed and diagonality. The predicted gait parameters were in good agreement with the measurements. Using the predicted gait parameters, the model was capable of detecting sow lameness, with an accuracy greater than 92%. However, the model was not tested on non-lame sows (negative subjects) because of the limitation of datasets. The capability of discriminating between non-lame and lame sows needs to be further studied with large datasets.

It should be noted that the model was developed and tested on relatively small size datasets and should be further tested on large datasets. In particular, large datasets covering a range of sow sizes should be used to test the model for its sensitivity to sow size because some gait parameters are dependent on sow size, such as stride length (McMahon, 1975). In the simulation model of this study, the sow size (length) was nominally represented by the total length of two rigid sticks (links 11-12 and 12-13 in Fig. 5.2), which approximated the pig trunk length in the model. Of the 81 non-lame sows tested, the average nominal length was 96±6 cm. The small standard deviation indicated that the tested sows coverd a relatively small size range. In addition, the simulation time step was limited by the frame rate of video recording (1/30 s). Durations of some movement phases, such as acceleration, were very short and only a few data points could be collected at the 1/30 s frame rate, which were not optimal to fit a 2nd order polynomial function. For example, an acceleration movement of 133.3 ms only has 4 data points. A higher speed camera could be used to improve the resolution of data extracted from the video recordings for the short-duration movements, in particular during acceleration and deceleration.

Although the 2D stick model developed in this study was primitive, it did show the potential of being used as a tool for managing sows. The commonly used method for lameness assessment in the commercial swine barns is visual locomotion scoring with a disadvantage of subjectivity. The ultimate goals are to develop a sophisticated model to determine sow gait from real-time video images and eventually use the model in commercial barns. A future scenario of application is to link the 2D stick model to a real-time video system to identify abnormal gait of sows for automatic detection of lameness. The video system could be installed at the entrance or exit of an electronic sow feeder for consistent images.

6.2 Overall Conclusions

This study provides a general perspective of the significant issues of concrete flooring in sow barns as related to animal welfare. The narrow slat (105 mm) and gap (19 mm) floor configuration, which was proven to be effective in improving sow comfort and leg health, had no negative impacts on manure drainage and in-barn air quality. This information could potentially help producers make decisions on slatted floor configuration in sow gestation barns.

An innovative method was developed in this study to assess the in-situ surface properties of concrete floors, which are closely related to the welfare of gestating sows in barns with slatted concrete floors. Surface friction and roughness of slatted concrete floors were significantly affected by the animal use of the floor. The new concrete floor had a dynamic coefficient of friction (DCOF) of 0.36, which is considered “non-slippery”. The DCOF decreased sharply (about 54%) in the first two weeks of use. This sharp decrease in floor friction was presumably due to accumulation of manure in the concrete pores. Manure stuck in the concrete pores resulted in reduction of interlocking between the asperities of the contact surface between the animal foot and the concrete. No significant differences in DCOF and floor roughness were observed among different areas of animal activities (dunging, high traffic, low traffic and sleeping) in the rooms, nor between two floor configurations (105-mm slats and 19-mm gaps versus 125-mm slats and 25-mm gaps).

Synovial joints in the animal body allow the body to perform various movements with inter-limb and inter-segmental coordination. A 2D stick model with 13 joints and 12 sticks adequately simulated the coordinated movements of a sow while walking on concrete floors. Movements of each joint could be modelled by combinations of 2^{nd} order polynomial functions and linear functions. The simulated movement coordinates of the joints during walking could be used to predict a selected set of gait parameters, including the stride length and stance time for fore- and hindlimbs, diagonality, back angle and walking speed. The stick model could be used to detect lameness of sows, with an accuracy greater than 92% for lameness detection.

7. Recommendations for Future Work

Slatted concrete floors are commonly used in sow barns. There is still a knowledge gap in the most effective slat and gap widths in terms of manure drainage and sow welfare. The feet lesions and lameness of sows could be related to slipperiness and abrasiveness of concrete floors. However, few studies have addressed the issues of in-situ surface properties of concrete floors or slippery-resistant floor solutions for sow housing. In terms of precision livestock farming, knowledge is still lacking in automatic and real-time lameness detection for sows. It would be a demanding and promising research topic in the future.

The surface properties of slatted concrete floors were measured while being used by sows during a 21-week test period in this study. The test period in this study was not long enough to observe any effect of chemical attack on the concrete and the changes in roughness. Further research is needed to investigate the floor surface properties changes in the long term to study the corrosive effect of manure on different locations of slatted concrete floors in sow barns. Even though there has been research done on the measurement of surface properties of concrete floors, these studies were mostly carried out in laboratories with simulated in-barn conditions, such as wet floor fouled by urine. Knowledge is still lacking with regard to the in-situ surface properties of concrete floors in animal barns. An interesting topic for future research would be to investigate the effect of manure (urine and feces) presence on the coefficient of friction (COF) of slatted concrete floors in pig barns by measuring the in-situ friction properties of floors befouled by manure to different extents. A critical minimum value of COF could be further recommended for concrete floors in pig barns based on observations of animal slip incidents or gait alterations using the proposed 2D stick model on the befouled concrete floors with different COF.

The 2D stick model for the simulation of sow walking and lameness detection developed in this thesis, while showing good performance, can certainly be improved. To improve the robustness of the model, future work could focus on building a larger scale database for model parameters, and more validation for threshold selection. A large-scale database could also be categorized to different ranges based on the sow size or parity and slatted floor configurations. Different body weights and floor configurations might result in different gait characteristics (McMahon, 1975; Devillers et al., 2019). Classifying different weight (size)-level sows on a range of slatted concrete floors might help improve the accuracy of model predictions. Some research (Grégoire et al., 2013) tried to associate different types of claw lesions with sow lameness (gait score) and found that severe lesions located under the foot affected some gait parameters more than those on the wall or the dew claws. Future work can also explore the possibility of using the model to identify the cause or severity of lameness based on the deviation(s) of movements of specific joint(s).

In this study, the stick model was based on a two-dimensional camera system to capture the movement of joints (markers) of sows. The three-dimensional camera system has been widely used for gait analysis of animals, which could be used in the future to obtain the 3D coordinates of markers on sows. The 3D camera system could ease the problem of calibration process of 2D system and capture the joint rotations in three-dimensional directions. In the future, the 3D camera system could be applied to test the feasibility of developing a 3D stick model to simulate sow walking.

Another possible direction for future research is to develop a real-time lameness detection system for sows by linking the 2D stick model to a video system, which could be installed at the entrance or exit of an electronic sow feeder for consistent images (Fig. 7.1). The system could raise an alarm for the farmer if the sow is detected as lame and allow early lameness detection and treatment for sows. The automatic real-time lameness detection system might be feasible for commercial barns with fair amount of space for the setting of the corridor and the computer vision system. However, the markers on sow body could be a practical challenge in actual barns. More advanced imaging analysis of identifying joints of sows without markers could be a solution.

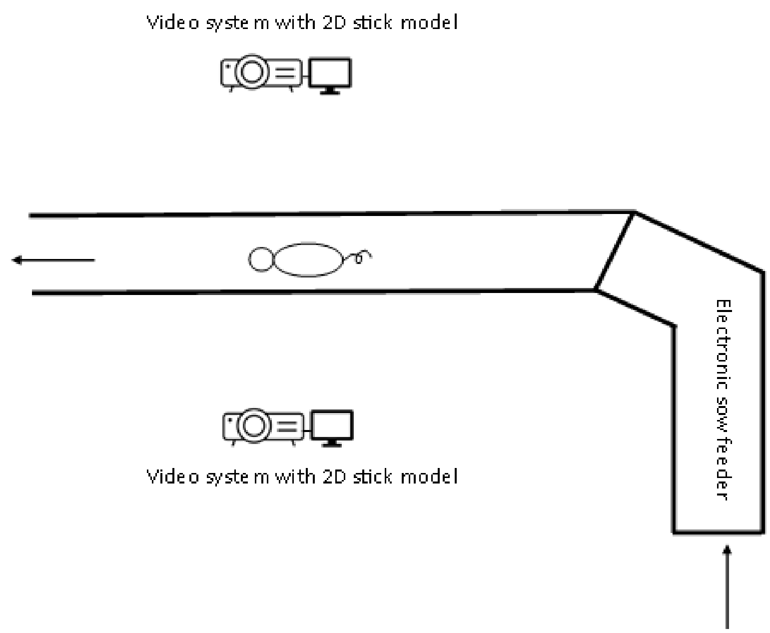


Figure 7. 1. Sketch of possible setup of the video system embedded with the 2D stick model in commercial barns

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Appendix A. MATLAB code for Gaussian filter applied on roughness data

```
clear;
data=[];
 detrend_data = data; %detrend(data)
trend = data - detrend_data;
mean(detrend_data);


lc=100;    % in count unit
dx=1;     % in count unit
alpha=0.4697; %default value
s = dx / (lc*alpha);
m = fix(sqrt(log(s*1000/dx)/pi)/s)+1;
n=length(detrend_data);
v = exp(-pi*s*s);
beta2=v*v;
count=1;
a=m;
b=n-m-1;
data1=s*detrend_data(a:b);
for count=1:m
      s=s*v;
      v=v*beta2;
   for c=2:(n-2*m-1)
      d=c+m-1-count;
      e=c+m-2+count;
      data1(c)=data1(c)+s*(detrend_data(d)+detrend_data(e));
   end;
```

```
end;


data2=detrend_data((a+1):(b-1));
data3=data1(2:(n-2*m-1));
roughness=data2-data3;
plot(roughness,'k');
hold on
xlabel('Counts');
ylabel('height (mm)');
Ra=mean(abs(roughness));
plot(detrend_data((a+1):(b-1)),'r');
plot(data1(2:(n-2*m-1)),'k');
%legend('Original Data','waviness')
```

Appendix B. MATLAB algorithm for sow gait simulation

```
%joint 1
P1=[];
x1s=P1(1); %starting point coordinates
y1s=P1(2);
a1ax=[];
alax=alax(randperm(numel(alax),1));
t1ax=[]; %acceleration when stepping x axis
tlax=tlax(randperm(numel(tlax),1));
v1x=[];
v1x=v1x(randperm(numel(v1x),1));
t1x=[]; %move in constant speed x axis
t1x=t1x(randperm(numel(t1x),1));
a1bx=[];
a1bx=a1bx(randperm(numel(a1bx),1));
t1bx=[]; %dececleration x axis
t1bx=t1bx(randperm(numel(t1bx),1));
a1ay=[];
a1ay=a1ay(randperm(numel(a1ay),1));
t1ay=[]; %acceleration y axis
t1ay=t1ay(randperm(numel(t1ay),1));
v1ay=[];
v1ay=v1ay(randperm(numel(v1ay),1));
t1ayc=[]; %constant speed up y axis
t1ayc=t1ayc(randperm(numel(t1ayc),1));
v1by=[];
v1by=v1by(randperm(numel(v1by),1));
t1byc=[]; %constant speed down y axis
t1byc=t1byc(randperm(numel(t1byc),1));
```

```
a1by=[];
a1by=a1by(randperm(numel(a1by),1));
t1by=[]; %deceleration y axis
t1by=t1by(randperm(numel(t1by),1));
t1=t1ax+t1x+t1bx; %total time for one step of point 1
%joint 2
P2=[];
x2s=P2(1);
y2s=P2(2);
a2ax=[];
a2ax=a2ax(randperm(numel(a2ax),1));
t2ax=[];
t2ax=t2ax(randperm(numel(t2ax),1));
v2x1=[];
v2x1=v2x1(randperm(numel(v2x1),1));
t2x1=[];
t2x1=t2x1(randperm(numel(t2x1),1));
a2bx=[];
a2bx=a2bx(randperm(numel(a2bx),1));
t2bx=[];
t2bx=t2bx(randperm(numel(t2bx),1));
v2y1=[];
v2y1=v2y1(randperm(numel(v2y1),1));
t2y1=[];
t2y1=t2y1(randperm(numel(t2y1),1));
v2y2=[];
v2y2=v2y2(randperm(numel(v2y2),1));
t2y2=[];
t2y2=t2y2(randperm(numel(t2y2),1));
v2x2=[];
v2x2=v2x2(randperm(numel(v2x2),1));
```

```
v2yc=[];
v2yc=v2yc(randperm(numel(v2yc),1));
t2=t2ax+t2x1+t2bx;
%joint 3
P3=[];
x3s=P3(1);
y3s=P3(2);
v3x=[];
v3x=v3x(randperm(numel(v3x),1));
a3y1=[];
a3y1=a3y1(randperm(numel(a3y1),1));
a3y2=[];
a3y2=a3y2(randperm(numel(a3y2),1));
a3y3=[];
a3y3=a3y3 (randperm(numel(a3y3),1));
%joint 6
P6=[];
x6s=P6(1); %starting coordinates
y6s=P6(2);
a6ax=[];
a6ax=a6ax(randperm(numel(a6ax),1));
t6ax=[]; %acceleration when stepping x axis
t6ax=t6ax(randperm(numel(t6ax),1));
v6x=[];
v6x=v6x(randperm(numel(v6x),1));
t6x=[]; %move in constant speed x axis
t6x=t6x(randperm(numel(t6x),1));
a6bx=[];
a6bx=a6bx(randperm(numel(a6bx),1));
t6bx=[]; %dececleration x axis
t6bx=t6bx(randperm(numel(t6bx),1));
```

```
a6ay=[];
a6ay=a6ay(randperm(numel(a6ay),1));
t6ay=[];
t6ay=t6ay(randperm(numel(t6ay),1));
a6by=[];
a6by=a6by(randperm(numel(a6by),1));
t6by=[];
t6by=t6by(randperm(numel(t6by),1));
v6ay=[];
v6ay=v6ay(randperm(numel(v6ay),1));
t6ayc=[];
t6ayc=t6ayc(randperm(numel(t6ayc),1));
v6by=[];
v6by=v6by(randperm(numel(v6by),1));
t6byc=[];
t6byc=t6byc(randperm(numel(t6byc),1));
t6=t6ax+t6x+t6bx;
%joint 7
P7=[];
x7s=P7(1); %starting coordinates
y7s=P7(2);
a7ax=[];
a7ax=a7ax(randperm(numel(a7ax),1));
t7ax=[];
t7ax=t7ax(randperm(numel(t7ax),1));
v7x1=[];
v7x1=v7x1(randperm(numel(v7x1),1));
t7x1=[];
t7x1=t7x1(randperm(numel(t7x1),1));
a7bx=[];
a7bx=a7bx(randperm(numel(a7bx),1));
```

```
t7bx=[];
t7bx=t7bx(randperm(numel(t7bx),1));
v7x2=[];
v7x2=v7x2(randperm(numel(v7x2),1));
a7ay=[];
a7ay=a7ay(randperm(numel(a7ay),1));
t7ay=[];
t7ay=t7ay(randperm(numel(t7ay),1));
v7y1=[];
v7y1=v7y1(randperm(numel(7y1),1));
t7y1=[];
t7y1=t7y1(randperm(numel(t7y1),1));
v7y2=[];
v7y2=v7y2(randperm(numel(v7y2),1));
t7y2=[];
t7y2=t7y2(randperm(numel(t7y2),1));
a7by=[];
a7by=a7by(randperm(numel(a7by),1));
t7by=[];
t7by=t7by(randperm(numel(t7by),1));
v7yc=[];
v7yc=v7yc(randperm(numel(v7yc),1));
v7y3=[];
v7y3=v7y3(randperm(numel(v7y3),1));
t7y3=[];
t7y3=t7y3(randperm(numel(t7y3),1));
v7yc=[];
v7yc=v7yc(randperm(numel(v7yc),1));
%joint 8
P8=[];
x8s=P8(1);
```

```
y8s=P8(2);
v8x=v3x;
a8y1=[];
a8y1= a8y1(randperm(numel(a8y1),1));
a8y2=[];
a8y2= a8y2(randperm(numel(a8y2),1));
a8y3=[];
a8y3= a8y3(randperm(numel(a8y3),1));
%joint 5
P5=[];
x5s=P5(1); %starting coordinates
y5s=P5(2);
a5ax=a1ax; %symmetrical as joint 1
t5ax=t1ax; %acceleration when stepping x axis
v5x=v1x;
t5x=t1x; %move in constant speed x axis
a5bx=a1bx;
t5bx=t1bx; %dececleration x axis
a5ay=a1by;
t5ay=t1by; %acceleration y axis
v5ay=v1ay;
t5ayc=t1ayc; %constant speed up y axis
v5by=v1by;
t5byc=t1byc; %constant speed down y axis
a5by=a1by;
t5by=t1by; %deceleration y axis
t5=t5ax+t5x+t5bx;
%point 4
P4=[];
x4s=P4(1);
y4s=P4(2);
```

```
a4ax=a2ax;
t4ax=t2ax;
v4x1=v2x1;
t4x1=t2x1;
a4bx=a2bx;
t4bx=t2bx;
v4y1=v2y1;
t4y1=t2y1;
v4y2=v2y2;
t4y2=t2y2;
v4x2=v2x2;
v4yc=v2yc;
t4=t4ax+t4x1+t4bx;
%point 10
P10=[];
a10ax=a6ax;
t10ax=t6ax; %acceleration when stepping x axis
v10x=v6x;
t10x=t6x; %move in constant speed x axis
a10bx=a6bx;
t10bx=t6bx; %dececleration x axis
a10ay=a6ay;
t10ay=t6ay;
a10by=a6by;
t10by=t6by;
v10ay=v6ay;
t10ayc=t6ay;
v10by=v6by;
t10byc=t6by;
t10=t10ax+t10x+t10bx;
```

```
%point 9
P9=[0];
x9s=P9(1); %starting coordinates
y9s=P9(2);
a9ax=a7ax;
t9ax=t7ax;
v9x1=v7x1;
t9x1=t7x1;
a9bx=a7bx;
t9bx=t7bx;
v9x2=v7x2;
a9ay=a7ay;
t9ay=t7ay;
v9y1=v7y1;
t9y1=t7y1;
v9y2=v7y2;
t9y2=t7y2;
a9by=a7by;
t9by=t7by;
v9yc=v7yc;
v9y3=v7y3;
t9y3=t7y3;
%point 11
P11=[];
x11s=P11(1);
y11s=P11(2);
v11x=v8x; % same speed as joint 3, 8
a11y1=[];
a11y1=a11y1(randperm(numel(a11y1),1));
a11y2=[];
a11y2=a11y2(randperm(numel(a11y2),1));
```

```
%point 13
P13=[];
x13s=P13(1);
y13s=P13(2);
v13x=v8x;
a13y1=[];
a13y1=a13y1(randperm(numel(a13y1),1));
a13y2=[];
a13y2=a13y2(randperm(numel(a13y2),1));
%point 12
P12=[];
x12s=P12(1);
y12s=P12(2);
v12x=v8x;
a12y1=[];
a12y1=a12y1(randperm(numel(a12y1),1));
a12y2=[];
a12y2=a11y2(randperm(numel(a12y2),1));
tg=[]; %gap time that one foot still on air, but next one already accelerate
tg=tg(randperm(numel(tg),1));
count=0;

for count=1:3
 for t=(1/30):(1/30):(t1+t6+t5+t10-3*tg)
     if t<=t1ay
     x1=x1s+0.5*a1ax*t^2;
     y1=y1s+0.5*a1ay*t^2;
     x2=x2s+0.5*a2ax*t^2;
     y2=y2s+v2y1*t;
     x3=x3s+v3x*t;
     y3=y3s+0.5*a3y1*t^2;
```

```
    x6=x6s;
    y6=y6s;% point 6 remains still
    x7=x7s+v7x2*t;
    y7=y7s+v7yc*t;
    x8=x8s+v8x*t;
    y8=y8s;
    x5=x5s;
    y5=y5s;
    x4=x4s+v4x2*t;
    y4=y4s+v4yc*t;
    x10=x10s;
    y10=y10s;
    x9=x9s+v9x2*t;
    y9=y9s+v9yc*t;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t^2);
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*t^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*t^2;
elseif t<=t1ax
    x1=x1s+0.5*a1ax*t^2;
    y1=y1s+0.5*a1ay*t1ay^2+v1ay*(t-t1ay);
    x2=x2s+0.5*a2ax*t^2;
    y2=y2s+v2y1*t;
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*t^2;
    x6=x6s;
    y6=y6s;
    x7=x7s+v7x2*t;
    y7=y7s+v7yc*t;
```

```
    x8=x8s+v8x*t;
    y8=y8s;
    x5=x5s;
    y5=y5s;
    x4=x4s+v4x2*t;
    y4=y4s+v4yc*t;;
    x10=x10s;
    y10=y10s;
    x9=x9s+v9x2*t;
    y9=y9s+v9yc*t;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t^2);
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*t^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*t^2;
elseif t<=t2y1 %added point2 later
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*(t-t1ax);
    y1=y1s+0.5*a1ay*t1ay^2+v1ay*(t-t1ay);
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*(t-t1ax);
    y2=y2s+v2y1*t;
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*t^2;
    x6=x6s;
    y6=y6s;
    x7=x7s+v7x2*t;
    y7=y7s+v7yc*t;
    x8=x8s+v8x*t;
    y8=y8s;
    x5=x5s;
    y5=y5s;
```

```
    x4=x4s+v4x2*t;
    y4=y4s+v4yc*t;
    x10=x10s;
    y10=y10s;
    x9=x9s+v9x2*t;
    y9=y9s+v9yc*t;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t^2);
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*t^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*t^2;
elseif t<=(t1ay+t1ayc)
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*(t-t1ax);
    y1=y1s+0.5*a1ay*t1ay^2+v1ay*(t-t1ay);
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*(t-t1ax);
    y2=y2s+v2y1*t2y1+v2y2*(t-t2y1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*t^2;
    x6=x6s;
    y6=y6s;
    x7=x7s+v7x2*t;
    y7=y7s+v7yc*t;
    x8=x8s+v8x*t;
    y8=y8s;
    x5=x5s;
    y5=y5s;
    x4=x4s+v4x2*t;
    y4=y4s+v4yc*t;
    x10=x10s;
    y10=y10s;
```

```
    x9=x9s+v9x2*t;
    y9=y9s+v9yc*t;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t^2);
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*t^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*t^2;
elseif t<=(t1ax+t1x)
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*(t-t1ax);
    y1=y1s+0.5*a1ay*t1ay^2+v1ay*t1ayc+v1by*(t-t1ay-t1ayc);
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*(t-t1ax);
    y2=y2s+v2y1*t2y1+v2y2*(t-t2y1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t-t1ay-t1ayc)^2;
    x6=x6s;
    y6=y6s;
    x7=x7s+v7x2*t;
    y7=y7s+v7yc*t;
    x8=x8s+v8x*t;
    y8=y8s;
    x5=x5s;
    y5=y5s;
    x4=x4s+v4x2*t;
    y4=y4s+v4yc*t;
    x10=x10s;
    y10=y10s;
    x9=x9s+v9x2*t;
    y9=y9s+v9yc*t;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t^2);
```

```
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*t^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t-t1ay-t1ayc)^2;
elseif t<=(t1ay+t1ayc+t1byc)
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t-t1ax-t1x)^2;
    y1=y1s+0.5*a1ay*t1ay^2+v1ay*t1ayc+v1by*(t-t1ay-t1ayc);
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t-t1ax-t1x)^2;
    y2=y2s+v2y1*t2y1+v2y2*(t-t2y1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t-t1ay-t1ayc)^2;
    x6=x6s+0.5*a6ax*(t-t1+tg)^2;
    y6=y6s+0.5*a6ay*(t-t1+tg)^2;
    x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t-t1ax-t1x)^2;
    y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t-t1+tg)^2;
    x8=x8s+v8x*t;
    y8=y8s+0.5*a8y1*(t-t1ax-t1x)^2;
    x5=x5s;
    y5=y5s;
    x4=x4s+v4x2*t;
    y4=y4s+v4yc*t;
    x10=x10s;
    y10=y10s;
    x9=x9s+v9x2*t;
    y9=y9s+v9yc*t;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t-t1ax-t1x)^2;
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t-t1ax-t1x)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t-t1ay-t1ayc)^2;
```

```
 elseif t<=(t1ax+t1x+t7ax)
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t-t1ax-t1x)^2;
    y1=y1s+0.5*a1ay*t1ay^2+v1ay*t1ayc+v1by*t1byc+0.5*a1by*(t-t1ay-t1ayc-
t1byc)^2;    %force y axis back to 0 at the end of step
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t-t1ax-t1x)^2;
    y2=y2s+v2y1*t2y1+v2y2*(t-t2y1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t-t1ay-t1ayc)^2;
    x6=x6s+0.5*a6ax*(t-t1+tg)^2;
    y6=y6s+0.5*a6ay*(t-t1+tg)^2;
    x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t-t1ax-t1x)^2;
    y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t-t1+tg)^2;
    x8=x8s+v8x*t;
    y8=y8s+0.5*a8y1*(t-t1ax-t1x)^2;
    x5=x5s;
    y5=y5s;
    x4=x4s+v4x2*t;
    y4=y4s+v4yc*t;
    x10=x10s;
    y10=y10s;
    x9=x9s+v9x2*t;
    y9=y9s+v9yc*t;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t-t1ax-t1x)^2;
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t-t1ax-t1x)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t-t1ay-t1ayc)^2;
 elseif t<=t1
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t-t1ax-t1x)^2;
```

```
    y1=y1s+0.5*a1ay*t1ay^2+v1ay*t1ayc+v1by*t1byc+0.5*a1by*(t-t1ay-t1ayc-
t1byc)^2;    %force y axis back to 0 at the end of step
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t-t1ax-t1x)^2;
    y2=y2s+v2y1*t2y1+v2y2*(t-t2y1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t-t1ay-t1ayc)^2;
    x6=x6s+0.5*a6ax*(t-t1+tg)^2;
    y6=y6s+0.5*a6ay*(t-t1+tg)^2;
    x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*(t-t1x-t1ax-t7ax);
    y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t-t1+tg)^2;
    x8=x8s+v8x*t;
    y8=y8s+0.5*a8y1*(t-t1ax-t1x)^2;
    x5=x5s;
    y5=y5s;
    x4=x4s+v4x2*t;
    y4=y4s+v4yc*t;
    x10=x10s;
    y10=y10s;
    x9=x9s+v9x2*t;
    y9=y9s+v9yc*t;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t-t1ax-t1x)^2;
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t-t1ax-t1x)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t-t1ay-t1ayc)^2;
 elseif t<=(t1-tg+t6ay)
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
    y1=0;% point 1 remains still
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
    y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
```

```
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t-t1)^2;
    x6=x6s+0.5*a6ax*(t6ax)^2+v6x*(t-t1+tg-t6ax);
    y6=y6s+0.5*a6ay*(t-t1+tg)^2;
    x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*(t-t1x-t1ax-t7ax);
    y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*(t-t1);
    x8=x8s+v8x*t;
    y8=y8s+0.5*a8y1*(t-t1ax-t1x)^2;
    x5=x5s;
    y5=y5s;
    x4=x4s+v4x2*t;
    y4=y4s+v4yc*t;
    x10=x10s;
    y10=y10s;
    x9=x9s+v9x2*t;
    y9=y9s+v9yc*t;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t-t1ax-t1x)^2;
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t-t1ax-t1x)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t-t1ay-t1ayc)^2;
elseif t<=(t1-tg+t6ay+t6by)
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
    y1=0;
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
    y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t-t1)^2;
    x6=x6s+0.5*a6ax*(t6ax)^2+v6x*(t-t1+tg-t6ax);
    y6=y6s+0.5*a6ay*(t6ay)^2+0.5*a6by*(t-t1+tg-t6ay)^2;
```

```
    x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*(t-t1x-t1ax-t7ax);
    y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*(t-t1);
    x8=x8s+v8x*t;
    y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t-t1+tg-t6ay)^2;
    x5=x5s;
    y5=y5s;
    x4=x4s+v4x2*t;
    y4=y4s;
    x10=x10s;
    y10=y10s;
    x9=x9s+v9x2*t;
    y9=y9s+v9yc*t;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t-t1ax-t1x)^2;
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t-t1ax-t1x)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t-t1ay-t1ayc)^2;
elseif t<=(t1-tg+t6ax+t6x)
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
    y1=0;
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
    y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t-t1)^2;
    x6=x6s+0.5*a6ax*(t6ax)^2+v6x*(t-t1+tg-t6ax);
    y6=y6s+0.5*a6ay*(t6ay)^2+0.5*a6by*(t6by)^2+v6ay*(t-t1+tg-t6ay-t6by);
    x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*(t-t1x-t1ax-t7ax);
    y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*(t-t1-t7y1);
    x8=x8s+v8x*t;
    y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t-t1+tg-t6ay)^2;
```

```
     x5=x5s;
     y5=y5s;
     x4=x4s+v4x2*t;
     y4=y4s+v4yc*t;
     x10=x10s;
     y10=y10s;
     x9=x9s+v9x2*t;
     y9=y9s+v9yc*t;
     x11=x11s+v11x*t;
     y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t-t1ax-t1x)^2;
     x13=x13s+v13x*t;
     y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t-t1ax-t1x)^2;
     x12=x12s+v12x*t;
     y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-
t1ayc)^2+0.5*a12y2*(t-t1+tg-t6ay-t6by)^2;
 elseif t<=(t1-2*tg+t6)
     x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
     y1=0;
     x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
     y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
     x3=x3s+v3x*t;
     y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t-t1)^2;
     x6=x6s+0.5*a6ax*(t6ax)^2+v6x*t6x+0.5*a6bx*(t-t1+tg-t6ax-t6x)^2;
     y6=y6s+0.5*a6ay*(t6ay)^2+0.5*a6by*(t6by)^2+v6ay*(t-t1+tg-t6ay-t6by);
     x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*t7x1+0.5*a7bx*(t-t1+tg-t7ax-t7x1)^2;
     y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*t7y2+0.5*a7by*(t-t1-t7y1-
t7y2)^2;
     x8=x8s+v8x*t;
     y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t-t1+tg-t6ay)^2;
     x5=x5s;
     y5=y5s;
```

```
      x4=x4s+v4x2*t;
      y4=y4s+v4yc*t;
      x10=x10s;
      y10=y10s;
      x9=x9s+v9x2*t;
      y9=y9s+v9yc*t;
      x11=x11s+v11x*t;
      y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t-t1ax-t1x)^2;
      x13=x13s+v13x*t;
      y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t-t1ax-t1x)^2;
      x12=x12s+v12x*t;
      y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-
t1ayc)^2+0.5*a12y2*(t-t1+tg-t6ay-t6by)^2;
 elseif t<=(t1-tg+t6ay+t6by+t6ayc)
      x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
      y1=0;
      x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
      y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
      x3=x3s+v3x*t;
      y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t6-
2*tg)^2+0.5*a3y1*(t-t1-t6+2*tg)^2;
      x6=x6s+0.5*a6ax*(t6ax)^2+v6x*t6x+0.5*a6bx*(t-t1+tg-t6ax-t6x)^2;
      y6=y6s+0.5*a6ay*(t6ay)^2+0.5*a6by*(t6by)^2+v6ay*(t-t1+tg-t6ay-t6by);
      x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*t7x1+0.5*a7bx*(t-t1+tg-t7ax-t7x1)^2;
      y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*t7y2+0.5*a7by*(t-t1-t7y1-
t7y2)^2;
      x8=x8s+v8x*t;
      y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t-t1+tg-t6ay)^2;
      x5=x5s+0.5*a5ax*(t-t1-t6+2*tg)^2;
      y5=y5s+0.5*a5ay*(t-t1-t6+2*tg)^2;
      x4=x4s+v4x2*(t1-2*tg+t6)+0.5*a4ax*(t-t1-t6+2*tg)^2;
```

```
    y4=y4s+v4yc*(t1+t6-2*tg)+v4y1*(t-t1-t6+2*tg);
    x10=x10s;
    y10=y10s;
    x9=x9s+v9x2*t;
    y9=y9s+v9yc*t;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a11y1*(t-
t1+2*tg-t6)^2;
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a13y2*(t-
t1+2*tg-t6)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-
t1ayc)^2+0.5*a12y2*(t-t1+tg-t6ay-t6by)^2;
 elseif t<=(t1-2*tg+t6+t5ay)
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
    y1=0;
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
    y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t6-
2*tg)^2+0.5*a3y1*(t-t1-t6+2*tg)^2;
    x6=x6s+0.5*a6ax*(t6ax)^2+v6x*t6x+0.5*a6bx*(t-t1+tg-t6ax-t6x)^2;
    y6=y6s+0.5*a6ay*(t6ay)^2+0.5*a6by*(t6by)^2+v6ay*t6ayc+v6by*(t-t1+tg-t6ay-t6by-
t6ayc);
    x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*t7x1+0.5*a7bx*(t-t1+tg-t7ax-t7x1)^2;

y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*t7y2+0.5*a7by*(t7by)^2+v7y3
*(t-t1-t7y1-t7y2-t7by);
    x8=x8s+v8x*t;
    y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t-t1+tg-t6ay)^2;
```

```
    x5=x5s+0.5*a5ax*(t-t1-t6+2*tg)^2;
    y5=y5s+0.5*a5ay*(t-t1-t6+2*tg)^2;
    x4=x4s+v4x2*(t1-2*tg+t6)+0.5*a4ax*(t-t1-t6+2*tg)^2;
    y4=y4s+v4yc*(t1+t6-2*tg)+v4y1*(t-t1-t6+2*tg);
    x10=x10s;
    y10=y10s;
    x9=x9s+v9x2*t;
    y9=y9s+v9yc*t;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a11y1*(t-
t1+2*tg-t6)^2;
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a13y2*(t-
t1+2*tg-t6)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-
t1ayc)^2+0.5*a12y2*(t-t1+tg-t6ay-t6by)^2;
 elseif t<=(t1-tg+t6)
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
    y1=0;
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
    y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t6-
2*tg)^2+0.5*a3y1*(t-t1-t6+2*tg)^2;
    x6=x6s+0.5*a6ax*(t6ax)^2+v6x*t6x+0.5*a6bx*(t-t1+tg-t6ax-t6x)^2;
    y6=y6s+0.5*a6ay*(t6ay)^2+0.5*a6by*(t6by)^2+v6ay*t6ayc+v6by*(t-t1+tg-t6ay-t6by-
t6ayc);
    x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*t7x1+0.5*a7bx*(t-t1+tg-t7ax-t7x1)^2;
```

```
y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*t7y2+0.5*a7by*(t7by)^2+v7y3
*(t-t1-t7y1-t7y2-t7by);
    x8=x8s+v8x*t;
    y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t-t1+tg-t6ay)^2;
    x5=x5s+0.5*a5ax*(t-t1-t6+2*tg)^2;
    y5=y5s+0.5*a5ay*(t5ay)^2+v5ay*(t-t1-t6+2*tg-t5ay);
    x4=x4s+v4x2*(t1-2*tg+t6)+0.5*a4ax*(t-t1-t6+2*tg)^2;
    y4=y4s+v4yc*(t1+t6-2*tg)+v4y1*(t-t1-t6+2*tg);
    x10=x10s;
    y10=y10s;
    x9=x9s+v9x2*t;
    y9=y9s+v9yc*t;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a11y1*(t-
t1+2*tg-t6)^2;
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a13y2*(t-
t1+2*tg-t6)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-
t1ayc)^2+0.5*a12y2*(t-t1+tg-t6ay-t6by)^2;
 elseif t<=(t1-2*tg+t6+t4y1) %added point 4
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
    y1=0;
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
    y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t6-
2*tg)^2+0.5*a3y1*(t-t1-t6+2*tg)^2;
    x6=x6s+0.5*a6ax*(t6ax)^2+v6x*t6x+0.5*a6bx*(t6bx)^2;
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```
    y6=0;
    x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*t7x1+0.5*a7bx*(t7bx)^2+v7x2*(t-
t1+tg-t6);

y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*t7y2+0.5*a7by*(t7by)^2+v7y3
*t7y3+v7yc*(t-t1+tg-t6);
    x8=x8s+v8x*t;
    y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t6by+t6ayc)^2+0.5*a8y3*(t-t1+tg-t6)^2;
    x5=x5s+0.5*a5ax*(t5ax)^2+v5x*(t-t1-t6+tg);
    y5=y5s+0.5*a5ay*(t5ay)^2+v5ay*(t-t1-t6+2*tg-t5ay);
    x4=x4s+v4x2*(t1-2*tg+t6)+0.5*a4ax*(t4ax)^2+v4x1*(t-t1-t6+tg);
    y4=y4s+v4yc*(t1+t6-2*tg)+v4y1*(t-t1-t6+2*tg);
    x10=x10s;
    y10=y10s;
    x9=x9s+v9x2*t;
    y9=y9s+v9yc*t;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a11y1*(t-
t1+2*tg-t6)^2;
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a13y2*(t-
t1+2*tg-t6)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-
t1ayc)^2+0.5*a12y2*(t-t1+tg-t6ay-t6by)^2;
 elseif t<=(t1-2*tg+t6+t5ay+t5ayc)
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
    y1=0;
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
    y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
    x3=x3s+v3x*t;
```

```
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t6-
2*tg)^2+0.5*a3y2*(t-t1-t6+2*tg)^2;
    x6=x6s+0.5*a6ax*(t6ax)^2+v6x*t6x+0.5*a6bx*(t6bx)^2;
    y6=0;
    x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*t7x1+0.5*a7bx*(t7bx)^2+v7x2*(t-
t1+tg-t6);

y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*t7y2+0.5*a7by*(t7by)^2+v7y3
*t7y3+v7yc*(t-t1+tg-t6);
    x8=x8s+v8x*t;
    y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t6by+t6ayc)^2+0.5*a8y3*(t-t1+tg-t6)^2;
    x5=x5s+0.5*a5ax*(t5ax)^2+v5x*(t-t1-t6+tg);
    y5=y5s+0.5*a5ay*(t5ay)^2+v5ay*(t-t1-t6+2*tg-t5ay);
    x4=x4s+v4x2*(t1-2*tg+t6)+0.5*a4ax*(t4ax)^2+v4x1*(t-t1-t6+tg);
    y4=y4s+v4yc*(t1+t6-2*tg)+v4y1*t4y1+v4y2*(t-t1-t6+2*tg-t4y1);
    x10=x10s;
    y10=y10s;
    x9=x9s+v9x2*t;
    y9=y9s+v9yc*t;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a11y1*(t-
t1+2*tg-t6)^2;
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a13y2*(t-
t1+2*tg-t6)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-
t1ayc)^2+0.5*a12y2*(t-t1+tg-t6ay-t6by)^2;
 elseif t<=(t1-2*tg+t6+t5ax+t5x)
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
    y1=0;
```

```
x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
x3=x3s+v3x*t;
y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t6-2*tg)^2+0.5*a3y1*(t5ay+t5ayc)^2+0.5*a3y2*(t-t1-t6+2*tg-t5ay-t5ayc)^2;
x6=x6s+0.5*a6ax*(t6ax)^2+v6x*t6x+0.5*a6bx*(t6bx)^2;
y6=0;
x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*t7x1+0.5*a7bx*(t7bx)^2+v7x2*(t-t1+tg-t6);

y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*t7y2+0.5*a7by*(t7by)^2+v7y3*t7y3+v7yc*(t-t1+tg-t6);
x8=x8s+v8x*t;
y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t6by+t6ayc)^2+0.5*a8y3*(t-t1+tg-t6)^2;
x5=x5s+0.5*a5ax*(t5ax)^2+v5x*(t-t1-t6+tg);
y5=y5s+0.5*a5ay*(t5ay)^2+v5ay*t5ayc+v5by*(t-t1-t6+2*tg-t5ay-t5ayc);
x4=x4s+v4x2*(t1-2*tg+t6)+0.5*a4ax*(t4ax)^2+v4x1*(t-t1-t6+tg);
y4=y4s+v4yc*(t1+t6-2*tg)+v4y1*t4y1+v4y2*(t-t1-t6+2*tg-t4y1);
x10=x10s;
y10=y10s;
x9=x9s+v9x2*t;
y9=y9s+v9yc*t;
x11=x11s+v11x*t;
y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a11y1*(t-t1+2*tg-t6)^2;
x13=x13s+v13x*t;
y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a13y2*(t-t1+2*tg-t6)^2;
x12=x12s+v12x*t;
y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-t1ayc)^2+0.5*a12y2*(t6-tg+t5ay+t5ayc-t6ay-t6by)^2+0.5*a12y1*(t-t1+2*tg-t6-t5ay-t5ayc)^2;
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 elseif t<=(t1-2*tg+t6+t5ay+t5ayc+t5byc)
     x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
     y1=0;
     x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
     y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
     x3=x3s+v3x*t;
     y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t6-
2*tg)^2+0.5*a3y1*(t5ay+t5ayc)^2+0.5*a3y2*(t-t1-t6+2*tg-t5ay-t5ayc)^2;
     x6=x6s+0.5*a6ax*(t6ax)^2+v6x*t6x+0.5*a6bx*(t6bx)^2;
     y6=0;
     x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*t7x1+0.5*a7bx*(t7bx)^2+v7x2*(t-
t1+tg-t6);

y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*t7y2+0.5*a7by*(t7by)^2+v7y3
*t7y3+v7yc*(t-t1+tg-t6);
     x5=x5s+0.5*a5ax*(t5ax)^2+v5x*t5x+0.5*a5bx*(t-t1-t6-t5+3*tg)^2;
     y5=y5s+0.5*a5ay*(t5ay)^2+v5ay*t5ayc+v5by*(t-t1-t6+2*tg-t5ay-t5ayc);
     x4=x4s+v4x2*(t1-2*tg+t6)+0.5*a4ax*(t4ax)^2+v4x1*t4x1+0.5*a4bx*(t-t1-t6+2*tg-t5ax-
t5x)^2;
     y4=y4s+v4yc*(t1+t6-2*tg)+v4y1*t4y1+v4y2*(t-t1-t6+2*tg-t4y1);
     x8=x8s+v8x*t;
     y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t6by+t6ayc)^2+0.5*a8y3*(t5-2*tg)^2+0.5*a8y1*(t-
t1+2*tg-t6-t5ax-t5x)^2;
     x10=x10s+0.5*a10ax*(t-t1-t6-t5+3*tg)^2;
     y10=y10s+0.5*a10ay*(t-t1-t6-t5+3*tg)^2;
     x9=x9s+v9x2*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ax*(t-t1-t6-t5+3*tg)^2;
     y9=y9s+v9yc*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ay*(t-t1-t6-t5+3*tg)^2;
     x11=x11s+v11x*t;
     y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t1-2*tg+t6-t1ax-
t1x)^2+0.5*a11y1*(t5ax+t5x)^2+0.5*a11y2*(t-t1+2*tg-t6-t5ax-t5x)^2;
     x13=x13s+v13x*t;
```

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    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t1-2*tg+t6-t1ax-
t1x)^2+0.5*a13y2*(t5ax+t5x)^2+0.5*a13y1*(t-t1+2*tg-t6-t5ax-t5x)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-
t1ayc)^2+0.5*a12y2*(t6-tg+t5ay+t5ayc-t6ay-t6by)^2+0.5*a12y1*(t-t1+2*tg-t6-t5ay-t5ayc)^2;
 elseif t<=(t1-3*tg+t6+t5+t9ax) %added point 9
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
    y1=0;
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
    y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t6-
2*tg)^2+0.5*a3y1*(t5ay+t5ayc)^2+0.5*a3y2*(t-t1-t6+2*tg-t5ay-t6ayc)^2;
    x6=x6s+0.5*a6ax*(t6ax)^2+v6x*t6x+0.5*a6bx*(t6bx)^2;
    y6=0;
    x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*t7x1+0.5*a7bx*(t7bx)^2+v7x2*(t-
t1+tg-t6);

y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*t7y2+0.5*a7by*(t7by)^2+v7y3
*t7y3+v7yc*(t-t1+tg-t6);
    x8=x8s+v8x*t;
    y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t6by+t6ayc)^2+0.5*a8y3*(t5-2*tg)^2+0.5*a8y1*(t-
t1+2*tg-t6-t5ax-t5x)^2;
    x5=x5s+0.5*a5ax*(t5ax)^2+v5x*t5x+0.5*a5bx*(t-t1-t6-t5+3*tg)^2;
    y5=y5s+0.5*a5ay*(t5ay)^2+v5ay*t5ayc+v5by*t5byc+0.5*a5by*(t-t1-t6+2*tg-t5ay-t5ayc-
t5byc)^2;
    x4=x4s+v4x2*(t1-2*tg+t6)+0.5*a4ax*(t4ax)^2+v4x1*t4x1+0.5*a4bx*(t-t1-t6+2*tg-t5ax-
t5x)^2;
    y4=y4s+v4yc*(t1+t6-2*tg)+v4y1*t4y1+v4y2*(t-t1-t6+2*tg-t4y1);
    x10=x10s+0.5*a10ax*(t-t1-t6-t5+3*tg)^2;
    y10=y10s+0.5*a10ay*(t-t1-t6-t5+3*tg)^2;
```

```
    x9=x9s+v9x2*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ax*(t-t1-t6-t5+3*tg)^2;
    y9=y9s+v9yc*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ay*(t-t1-t6-t5+3*tg)^2;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t1-2*tg+t6-t1ax-
t1x)^2+0.5*a11y1*(t5ax+t5x)^2+0.5*a11y2*(t-t1+2*tg-t6-t5ax-t5x)^2;
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t1-2*tg+t6-t1ax-
t1x)^2+0.5*a13y2*(t5ax+t5x)^2+0.5*a13y1*(t-t1+2*tg-t6-t5ax-t5x)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-
t1ayc)^2+0.5*a12y2*(t6-tg+t5ay+t5ayc-t6ay-t6by)^2+0.5*a12y1*(t-t1+2*tg-t6-t5ay-t5ayc)^2;
 elseif t<=(t1-3*tg+t6+t5+t5bx)
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
    y1=0;
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
    y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t6-
2*tg)^2+0.5*a3y1*(t5ay+t5ayc)^2+0.5*a3y2*(t-t1-t6+2*tg-t5ay-t5ayc)^2;
    x6=x6s+0.5*a6ax*(t6ax)^2+v6x*t6x+0.5*a6bx*(t6bx)^2;
    y6=0;
    x7=x7s+0.5*a7ax*(t7ax)^2+v7x1*t7x1+0.5*a7bx*(t7bx)^2+v7x2*(t-t1+tg-t6);

y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*t7y2+0.5*a7by*(t7by)^2+v7y3
*t7y3+v7yc*(t-t1+tg-t6);
    x8=x8s+v8x*t;
    y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t6by+t6ayc)^2+0.5*a8y3*(t5-2*tg)^2+0.5*a8y1*(t-
t1+2*tg-t6-t5ax-t5x)^2;
    x5=x5s+0.5*a5ax*(t5ax)^2+v5x*t5x+0.5*a5bx*(t-t1-t6-t5+3*tg)^2;
    y5=y5s+0.5*a5ay*(t5ay)^2+v5ay*t5ayc+v5by*t5byc+0.5*a5by*(t-t1-t6+2*tg-t5ay-t5ayc-
t5byc)^2;
```

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    x4=x4s+v4x2*(t1-2*tg+t6)+0.5*a4ax*(t4ax)^2+v4x1*t4x1+0.5*a4bx*(t-t1-t6+2*tg-t5ax-t5x)^2;
    y4=y4s+v4yc*(t1+t6-2*tg)+v4y1*t4y1+v4y2*(t-t1-t6+2*tg-t4y1);
    x10=x10s+0.5*a10ax*(t-t1-t6-t5+3*tg)^2;
    y10=y10s+0.5*a10ay*(t-t1-t6-t5+3*tg)^2;
    x9=x9s+v9x2*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ax*(t9ax)^2+v9x1*(t-t1-t6-t5+3*tg-t9ax);
    y9=y9s+v9yc*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ay*(t-t1-t6-t5+3*tg)^2;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a11y1*(t5ax+t5x)^2+0.5*a11y2*(t-t1+2*tg-t6-t5ax-t5x)^2;
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a13y2*(t5ax+t5x)^2+0.5*a13y1*(t-t1+2*tg-t6-t5ax-t5x)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-t1ayc)^2+0.5*a12y2*(t6-tg+t5ay+t5ayc-t6ay-t6by)^2+0.5*a12y1*(t-t1+2*tg-t6-t5ay-t5ayc)^2;
 elseif t<=(t1-3*tg+t6+t5+t10ay)
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
    y1=0;
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
    y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t6-2*tg)^2+0.5*a3y1*(t5ay+t5ayc)^2+0.5*a3y2*(t5-t5ay-t5ayc)^2+0.5*a3y3*(t-t1-t6+2*tg-t5)^2;
    x6=x6s+0.5*a6ax*(t6ax)^2+v6x*t6x+0.5*a6bx*(t6bx)^2;
    y6=0;
    x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*t7x1+0.5*a7bx*(t7bx)^2+v7x2*(t-t1+tg-t6);

y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*t7y2+0.5*a7by*(t7by)^2+v7y3*t7y3+v7yc*(t-t1+tg-t6);
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```
    x8=x8s+v8x*t;
    y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t6by+t6ayc)^2+0.5*a8y3*(t5-2*tg)^2+0.5*a8y1*(t-t1+2*tg-t6-t5ax-t5x)^2;
    x5=x5s+0.5*a5ax*(t5ax)^2+v5x*t5x+0.5*a5bx*(t5bx)^2;
    y5=0;
    x4=x4s+v4x2*(t1-2*tg+t6)+0.5*a4ax*(t4ax)^2+v4x1*t4x1+0.5*a4bx*(t4bx)^2+v4x2*(t-t1-t6+2*tg-t5);
    y4=y4s+v4yc*(t1+t6-2*tg)+v4y1*t4y1+v4y2*(t5+t5bx-tg-t4y1)+v4yc*(t-t1+3*tg-t6-t5-t5bx);
    x10=x10s+0.5*a10ax*(t10ax)^2+v10x*(t-t1-t6-t5+3*tg-t10ax);
    y10=y10s+0.5*a10ay*(t-t1-t6-t5+3*tg)^2;
    x9=x9s+v9x2*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ax*(t9ax)^2+v9x1*(t-t1-t6-t5+3*tg-t9ax);
    y9=y9s+v9yc*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ay*(t9ay)^2+v9y1*(t-t1-t6-t5+3*tg-t9ay);
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a11y1*(t5ax+t5x)^2+0.5*a11y2*(t-t1+2*tg-t6-t5ax-t5x)^2;
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a13y2*(t5ax+t5x)^2+0.5*a13y1*(t-t1+2*tg-t6-t5ax-t5x)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-t1ayc)^2+0.5*a12y2*(t6-tg+t5ay+t5ayc-t6ay-t6by)^2+0.5*a12y1*(t-t1+2*tg-t6-t5ay-t5ayc)^2;
 elseif t<=(t1-3*tg+t6+t5+t10ay+t10by)
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
    y1=0;
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
    y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t6-2*tg)^2+0.5*a3y1*(t5ay+t5ayc)^2+0.5*a3y2*(t5-t5ay-t5ayc)^2+0.5*a3y3*(t-t1-t6+2*tg-t5)^2;
    x6=x6s+0.5*a6ax*(t6ax)^2+v6x*t6x+0.5*a6bx*(t6bx)^2;
```

```
y6=0;
x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*t7x1+0.5*a7bx*(t7bx)^2+v7x2*(t-t1+tg-t6);
y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*t7y2+0.5*a7by*(t7by)^2+v7y3*t7y3+v7yc*(t-t1+tg-t6);
x8=x8s+v8x*t;
y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t6by+t6ayc)^2+0.5*a8y3*(t5-2*tg)^2+0.5*a8y1*(t10ax)^2+0.5*a8y2*(t-t1-t6-t5+3*tg-t10ay)^2;
x5=x5s+0.5*a5ax*(t5ax)^2+v5x*t5x+0.5*a5bx*(t5bx)^2;
y5=0;
x4=x4s+v4x2*(t1-2*tg+t6)+0.5*a4ax*(t4ax)^2+v4x1*t4x1+0.5*a4bx*(t4bx)^2+v4x2*(t-t1-t6+2*tg-t5);
y4=y4s+v4yc*(t1+t6-2*tg)+v4y1*t4y1+v4y2*(t5+t5bx-tg-t4y1)+v4yc*(t-t1+3*tg-t6-t5-t5bx);
x10=x10s+0.5*a10ax*(t10ax)^2+v10x*(t-t1-t6-t5+3*tg-t10ax);
y10=y10s+0.5*a10ay*(t10ax)^2+0.5*a10by*(t-t1-t6-t5+3*tg-t10ay)^2;
x9=x9s+v9x2*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ax*(t9ax)^2+v9x1*(t-t1-t6-t5+3*tg-t9ax);
y9=y9s+v9yc*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ay*(t9ay)^2+v9y1*(t-t1-t6-t5+3*tg-t9ay);
x11=x11s+v11x*t;
y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a11y1*(t5ax+t5x)^2+0.5*a11y2*(t-t1+2*tg-t6-t5ax-t5x)^2;
x13=x13s+v13x*t;
y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a13y2*(t5ax+t5x)^2+0.5*a13y1*(t-t1+2*tg-t6-t5ax-t5x)^2;
x12=x12s+v12x*t;
y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-t1ayc)^2+0.5*a12y2*(t6-tg+t5ay+t5ayc-t6ay-t6by)^2+0.5*a12y1*(t-t1+2*tg-t6-t5ay-t5ayc)^2;
elseif t<=(t1-3*tg+t6+t5+t10ax+t10x)
x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
y1=0;
```

x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);

y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);

x3=x3s+v3x*t;

y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t6-2*tg)^2+0.5*a3y1*(t5ay+t5ayc)^2+0.5*a3y2*(t5-t5ay-t5ayc)^2+0.5*a3y3*(t-t1-t6+2*tg-t5)^2;

x6=x6s+0.5*a6ax*(t6ax)^2+v6x*t6x+0.5*a6bx*(t6bx)^2;

y6=0;

x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*t7x1+0.5*a7bx*(t7bx)^2+v7x2*(t-t1+tg-t6);

y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*t7y2+0.5*a7by*(t7by)^2+v7y3*t7y3+v7yc*(t-t1+tg-t6);

x8=x8s+v8x*t;

y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t6by+t6ayc)^2+0.5*a8y3*(t5-2*tg)^2+0.5*a8y1*(t10ax)^2+0.5*a8y2*(t-t1-t6-t5+3*tg-t10ay)^2;

x5=x5s+0.5*a5ax*(t5ax)^2+v5x*t5x+0.5*a5bx*(t5bx)^2;

y5=0;

x4=x4s+v4x2*(t1-2*tg+t6)+0.5*a4ax*(t4ax)^2+v4x1*t4x1+0.5*a4bx*(t4bx)^2+v4x2*(t-t1-t6+2*tg-t5);

y4=y4s+v4yc*(t1+t6-2*tg)+v4y1*t4y1+v4y2*(t5+t5bx-tg-t4y1)+v4yc*(t-t1+3*tg-t6-t5-t5bx);

x10=x10s+0.5*a10ax*(t10ax)^2+v10x*(t-t1-t6-t5+3*tg-t10ax);

y10=y10s+0.5*a10ay*(t10ax)^2+0.5*a10by*(t10by)^2+v10ay*(t-t1-t6-t5+3*tg-t10ay-t10by);

x9=x9s+v9x2*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ax*(t9ax)^2+v9x1*(t-t1-t6-t5+3*tg-t9ax);

y9=y9s+v9yc*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ay*(t9ay)^2+v9y1*t9y1+v9y2*(t-t1-t6-t5+3*tg-t9ay-t9y1);

x11=x11s+v11x*t;

y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a11y1*(t5ax+t5x)^2+0.5*a11y2*(t-t1+2*tg-t6-t5ax-t5x)^2;

x13=x13s+v13x*t;

```
    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t1-2*tg+t6-t1ax-
t1x)^2+0.5*a13y2*(t5ax+t5x)^2+0.5*a13y1*(t-t1+2*tg-t6-t5ax-t5x)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-
t1ayc)^2+0.5*a12y2*(t6-tg+t5ay+t5ayc-t6ay-t6by)^2+0.5*a12y1*(t5+t10ay+t10by-tg-t5ay-
t5ayc)^2+0.5*a12y2*(t-t1+3*tg-t6-t5-t10ay-t10by)^2;
 elseif t<=(t1-3*tg+t6+t5+t10ay+t10by+t10ayc)
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
    y1=0;
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
    y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t6-
2*tg)^2+0.5*a3y1*(t5ay+t5ayc)^2+0.5*a3y2*(t5-t5ay-t5ayc)^2+0.5*a3y3*(t-t1-t6+2*tg-t5)^2;
    x6=x6s+0.5*a6ax*(t6ax)^2+v6x*t6x+0.5*a6bx*(t6bx)^2;
    y6=0;
    x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*t7x1+0.5*a7bx*(t7bx)^2+v7x2*(t-
t1+tg-t6);

y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*t7y2+0.5*a7by*(t7by)^2+v7y3
*t7y3+v7yc*(t-t1+tg-t6);
    x8=x8s+v8x*t;
    y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t6by+t6ayc)^2+0.5*a8y3*(t5-
2*tg)^2+0.5*a8y1*(t10ax)^2+0.5*a8y2*(t-t1-t6-t5+3*tg-t10ay)^2;
    x5=x5s+0.5*a5ax*(t5ax)^2+v5x*t5x+0.5*a5bx*(t5bx)^2;
    y5=0;
    x4=x4s+v4x2*(t1-2*tg+t6)+0.5*a4ax*(t4ax)^2+v4x1*t4x1+0.5*a4bx*(t4bx)^2+v4x2*(t-t1-
t6+2*tg-t5);
    y4=y4s+v4yc*(t1+t6-2*tg)+v4y1*t4y1+v4y2*(t5+t5bx-tg-t4y1)+v4yc*(t-t1+3*tg-t6-t5-
t5bx);
    x10=x10s+0.5*a10ax*(t10ax)^2+v10x*t10x+0.5*a10bx*(t-t1-t6-t5+3*tg-t10ax-t10x)^2;
```

```
    y10=y10s+0.5*a10ay*(t10ax)^2+0.5*a10by*(t10by)^2+v10ay*(t-t1-t6-t5+3*tg-t10ay-t10by);
    x9=x9s+v9x2*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ax*(t9ax)^2+v9x1*t9x1+0.5*a9bx*(t-t1-t6-t5+3*tg-t9ax-t9x1)^2;
    y9=y9s+v9yc*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ay*(t9ay)^2+v9y1*t9y1+v9y2*t9y2+0.5*a9by*(t-t1-t6-t5+3*tg-t9ax-t9x1)^2;
    x11=x11s+v11x*t;
    y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a11y1*(t5ax+t5x)^2+0.5*a11y2*(t-t1+2*tg-t6-t5ax-t5x)^2;
    x13=x13s+v13x*t;
    y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a13y2*(t5ax+t5x)^2+0.5*a13y1*(t-t1+2*tg-t6-t5ax-t5x)^2;
    x12=x12s+v12x*t;
    y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-t1ayc)^2+0.5*a12y2*(t6-tg+t5ay+t5ayc-t6ay-t6by)^2+0.5*a12y1*(t5+t10ay+t10by-tg-t5ay-t5ayc)^2+0.5*a12y2*(t-t1+3*tg-t6-t5-t10ay-t10by)^2;
 else
    x1=x1s+0.5*a1ax*(t1ax)^2+v1x*t1x+0.5*a1bx*(t1bx)^2;
    y1=0;
    x2=x2s+0.5*a2ax*(t1ax)^2+v2x1*t1x+0.5*a2bx*(t1bx)^2+v2x2*(t-t1);
    y2=y2s+v2y1*t2y1+v2y2*(t1-t2y1)+v2yc*(t-t1);
    x3=x3s+v3x*t;
    y3=y3s+0.5*a3y1*(t1ay+t1ayc)^2+0.5*a3y2*(t1-t1ay-t1ayc)^2+0.5*a3y3*(t6-2*tg)^2+0.5*a3y1*(t5ay+t5ayc)^2+0.5*a3y2*(t5-t5ay-t5ayc)^2+0.5*a3y3*(t-t1-t6+2*tg-t5)^2;
    x6=x6s+0.5*a6ax*(t6ax)^2+v6x*t6x+0.5*a6bx*(t6bx)^2;
    y6=0;
    x7=x7s+v7x2*(t1ax+t1x)+0.5*a7ax*(t7ax)^2+v7x1*t7x1+0.5*a7bx*(t7bx)^2+v7x2*(t-t1+tg-t6);
```

y7=y7s+v7yc*(t1ax+t1x)+0.5*a7ay*(t7ay)^2+v7y1*t7y1+v7y2*t7y2+0.5*a7by*(t7by)^2+v7y3*t7y3+v7yc*(t-t1+tg-t6);

x8=x8s+v8x*t;

y8=y8s+0.5*a8y1*(t6ay)^2+0.5*a8y2*(t6by+t6ayc)^2+0.5*a8y3*(t5-2*tg)^2+0.5*a8y1*(t10ax)^2+0.5*a8y2*(t-t1-t6-t5+3*tg-t10ay)^2;

x5=x5s+0.5*a5ax*(t5ax)^2+v5x*t5x+0.5*a5bx*(t5bx)^2;

y5=0;

x4=x4s+v4x2*(t1-2*tg+t6)+0.5*a4ax*(t4ax)^2+v4x1*t4x1+0.5*a4bx*(t4bx)^2+v4x2*(t-2*t1-t6+2*tg);

y4=y4s+v4yc*(t1+t6-2*tg)+v4y1*t4y1+v4y2*(t5+t5bx-tg-t4y1)+v4yc*(t-t1+3*tg-t6-t5-t5bx);

x10=x10s+0.5*a10ax*(t10ax)^2+v10x*t10x+0.5*a10bx*(t-t1-t6-t5+3*tg-t10ax-t10x)^2;

y10=y10s+0.5*a10ay*(t10ax)^2+0.5*a10by*(t10by)^2+v10ay*t10ayc+v10by*(t-t1-t6-t5+3*tg-t10ay-t10by-t10ayc);

x9=x9s+v9x2*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ax*(t9ax)^2+v9x1*t9x1+0.5*a9bx*(t-t1-t6-t5+3*tg-t9ax-t9x1)^2;

y9=y9s+v9yc*(t1-2*tg+t6+t5ax+t5x)+0.5*a9ay*(t9ay)^2+v9y1*t9y1+v9y2*t9y2+0.5*a9by*(t9by)^2+v9y3*(t-t1-t6-t5+3*tg-t9ax-t9x1-t9by);

x11=x11s+v11x*t;

y11=y11s+0.5*a11y1*(t1ax+t1x)^2+0.5*a11y2*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a11y1*(t5ax+t5x)^2+0.5*a11y2*(t-t1+2*tg-t6-t5ax-t5x)^2;

x13=x13s+v13x*t;

y13=y13s+0.5*a13y2*(t1ax+t1x)^2+0.5*a13y1*(t1-2*tg+t6-t1ax-t1x)^2+0.5*a13y2*(t5ax+t5x)^2+0.5*a13y1*(t-t1+2*tg-t6-t5ax-t5x)^2;

x12=x12s+v12x*t;

y12=y12s+0.5*a12y2*(t1ay+t1ayc)^2+0.5*a12y1*(t1-tg+t6ay+t6by-t1ay-t1ayc)^2+0.5*a12y2*(t6-tg+t5ay+t5ayc-t6ay-t6by)^2+0.5*a12y1*(t5+t10ay+t10by-tg-t5ay-t5ayc)^2+0.5*a12y2*(t-t1+3*tg-t6-t5-t10ay-t10by)^2;

```
    end;

plot(x1, y1,'r*');       %Plot the red dot
hold on
plot(x2, real(y2),'ro');

plot(x3, real(y3),'r*');

plot(x3, real(y3),'bo');

plot(x6, y6,'g*');

plot(x7, y7,'go');

plot(x8, y8,'g*');

plot(x8, y8,'ko');

plot(x5, y5,'bo');

plot(x4, y4,'b*');

plot(x10, y10,'ko');

plot(x9, y9,'k*');

plot(x11, y11,'c*');

plot(x13, y13,'c*');

plot(x12, real(y12),'c*');
```

```
plot([x1 x2],[y1 y2]);

plot([x2 x3],[y2 y3]);

plot([x5 x4],[y5 y4]);

plot([x4 x3],[y4 y3]);

plot([x6 x7],[y6 y7]);

plot([x7 x8],[y7 y8]);

plot([x10 x9],[y10 y9]);

plot([x9 x8],[y9 y8]);

plot([x3 x11],[y3 y11]);

plot([x11 x12],[y11 y12]);

plot([x12 x13],[y12 y13]);

plot([x8 x13],[y8 y13]);
hold off
axis([0 6 0 1])
drawnow();
pause(0.5)
end;
x1s=x1;
y1s=y1;
```

```
x2s=x2;
y2s=y2;
x3s=x3;
y3s=y3;
x6s=x6;
y6s=y6;
x7s=x7;
y7s=y7;
x8s=x8;
y8s=y8;
x5s=x5;
y5s=y5;
x4s=x4;
y4s=y4;
x10s=x10;
y10s=y10;
x9s=x9;
y9s=y9;
x11s=x11;
y11s=y11;
x13s=x13;
y13s=y13;
x12s=x12;
y12s=y12;
end;
t=3*(t1+t6+t5+t10-3*tg);
```

Appendix C: Devillers et al. (2020)

Determining an effective slat and gap width of flooring for group sow housing, considering both sow comfort and ease of manure management

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Abstract

The majority of slatted concrete floors for group-housed sows are designed for ease of manure management. However, such floors can be associated with sows' lying and walking discomfort, feet injuries and lameness. This study was designed to evaluate the impacts of a narrower slat and gap widths flooring on sow comfort and behaviour as well as manure management. Gilts were followed through two gestations housed on either a concrete floor with a slat width of 105 mm and gaps of 19 mm (Test; n = 25) or a flooring with a slat width of 125 mm and gaps of 25 mm (Control; n = 24) and fed with electronic sow feeders. Slat friction, air temperature, humidity and ammonia concentrations were recorded throughout. Floor and animal cleanliness were assessed weekly. For each sow gait score, limb weight distribution, postural behaviour, feet lesions, time budget of activities, body weight, backfat, and reproductive performances were measured at beginning and end of gestation. Air environment values remained within acceptable limits, with no significant (P>0.05) differences between Test and Control rooms. Floor and animal cleanliness were similar for Test and Control. The coefficient of friction of floors decreased markedly within the first week of occupancy then stabilized throughout gestation without differences between treatments. The overall incidence of lameness was similar for Test (16.7%) and Control (14.4%), but more Control sows required analgesic treatment. The severity of heel overgrowth and erosion was greater on front and rear feet and for wall cracks on rear feet of Control sows. Some effects were evident within one week of being on the Control floor and therefore may have been pre-existing. Control sows spent more time weight-shifting in late gestation and showed more variability in the weight applied on hind legs. Control sows spent more time standing at week 6, being passive at week 10 and in social interactions at the end of gestation 1 than Test sows. There were no significant (P>0.05) differences in frequency of posture changes, sow body weight, backfat and reproductive performance between treatments. While results did not show marked differences in animal performances, sows on the wider (Control) slat and gap flooring had higher feet lesion scores and indicators of greater discomfort while standing. Therefore, the narrower slat and gap widths tested may provide benefits in terms of feet health and sow comfort without compromising manure management and air quality.

Keywords: concrete slatted floor, air quality, ammonia, lameness, feet lesions, behaviour

1. Introduction

In North America, the transition from individual stall to group-housing of sows during gestation has tended to maintain the slatted floor systems associated with conventional slurry-based manure handling. While the impact of slat and gap widths on foot health may not be as apparent in stall-housed sows, ease of locomotion is imperative for group-housed sows to access essential pen resources and maintain their position in the social hierarchy. Therefore, the move to group housing makes decisions on flooring critical for success.

Inadequate flooring can be a major cause of sow lying and walking discomfort, lameness and hoof injuries (Barnett et al, 2001; Maes et al., 2016), the resulting distress and pain leading to suboptimal performance and early culling. Leg and hoof/claw injuries and lameness are major reasons for culling sows, particularly in group housing (Pluym et al. 2011). Feet and leg soundness are particularly impacted by concrete slatted floors (Kilbride et al., 2009a), which are associated with increased incidence of lameness, especially after regrouping-induced fighting (Anil et al., 2006). Further, sows housed on slatted floors show more claw injuries and lameness than ones housed on partially slatted (Vermeij et al., 2009) or solid floors (Heinonen et al., 2006). While slatted floors are designed for effective drainage of manure to achieve cleaner and more hygienic floors, and decrease the total pen space needed, considerations must be given to other aspects of sow health and well-being. Interestingly, although totally or partially slatted concrete flooring is the norm for loose sow housing in North America (and many other countries), scientifically-derived information on the most suitable slat and gap widths is not readily available. Even the origin of the requirements in the European Union of a minimum slat width of 80 mm and gaps no greater than 20 mm (Council of the European Union, 2008) is not clear. The Canadian code of practice for pigs provides no specific values but advises that slat widths should maximize the area of sole contact and gap widths be appropriate for the sizes of pigs (National Farm Animal Care Council, 2014). However, experiential information in Canada favours a concrete slat width of 127 mm with gap width of 20 mm for sow flooring (Peet, 2011), though gap widths of 25 mm are common. Functionally, slats need to be wide enough with surface characteristics suitable for sows to walk comfortably and gap widths should allow manure passage, but not catch toes or claws.

With these factors in mind, research was initiated to investigate different slat and gap widths to determine the best design for the sow while maintaining pen cleanliness and air quality. By using kinematic analysis of sows walking on flooring of various slat (85, 105 or 125 mm) and gap width (19, 22 or 25 mm) combinations it was determined that a) more gait parameters of small non-lame sows were altered by floor design than in large lame sows, the implication being the smaller footed animals, such as gilts and early parity sows, are more vulnerable to slat/gap width variations; and b) slat widths of 105 - 125 mm with gap widths of 19 - 22 mm modified sows' gaits the least compared to solid concrete floor (Devillers et al., 2019). In order to determine the long-term effect, in-barn studies with group-housed sows were needed. The objectives of the current research were to compare animal performance, lameness and behaviour during two gestations on a slatted flooring which least affected the sows' gaits in the previous study (Test floor) to sows housed on a more conventional slatted flooring configuration (Control floor) starting with nulliparous sows. Floor characteristics, pen cleanliness and air quality were monitored throughout.

2. Material and methods

2.1 Floor treatment

In this study, the commonly used configuration of 125 mm slat with 25 mm gap was used as the Control floor and the 105 mm slat with 19 mm gap was the Test floor. Both floors had similar permeability (Control: 16.7%; Test: 15.3%). The two slatted concrete floors were newly manufactured (Barkman Concrete, Steinbach, Manitoba) and installed in two identical rooms, each containing a pen with the slatted floor and a NEDAP electronic sow feeder (New Standard Ag Inc., Saint Andrews, MB). Pregnant sows were housed in each room, allowing 2.04 m^2/animal, from 5 weeks to 15 weeks of gestation during two consecutive gestations cycles.

2.1.1 Floor friction

Friction of the slat surfaces was measured throughout the test periods to quantify the slipperiness (slip resistance) of the slatted concrete floors in both rooms. A surface tester was designed and constructed to measure surface friction and roughness. The tester consisted of a sliding carriage that can move over a 19-inch (48.25 cm) path horizontally at a speed of 0.7 mm/s (Figure 1). A 50 × 50 mm piece of high-density polyethylene (HDPE) was used as the test foot to simulate a sow foot. As the HDPE foot was pulled over a selected floor area, a dead weight of 10.3 kg was used to apply a vertical (normal) load on the HDPE foot and the pulling (friction) force was measured by a load cell (Omega LCEB-50, Omega Engineering Inc., Norwalk, CT, USA) mounted on the carriage. The load cell had a maximum range of 222.5 N (50 lb), linearity ±0.03% full scale, repeatability ±0.01% full scale, and creep (after 20 min) ±0.15%. For each test, the test foot was pulled over a 48.25 cm path, in both forward and backward directions. For each direction of travel, 690 readings of frictional force were taken. The dynamic coefficient of friction (DCOF) for HDPE was calculated (Nilsson, 1988) as an indicator of floor slipperiness by the following equation:

$$DCOF = \frac{F_k}{F_n} = \frac{F_k}{mg}$$

where,

F_k is the pulling (friction) force measured by load cell, N;

F_n is the applied normal force or load, N;

m is the mass of dead weight placed on the HDPE foot, kg;

g is gravitational constant, 9.8 m/s^2.

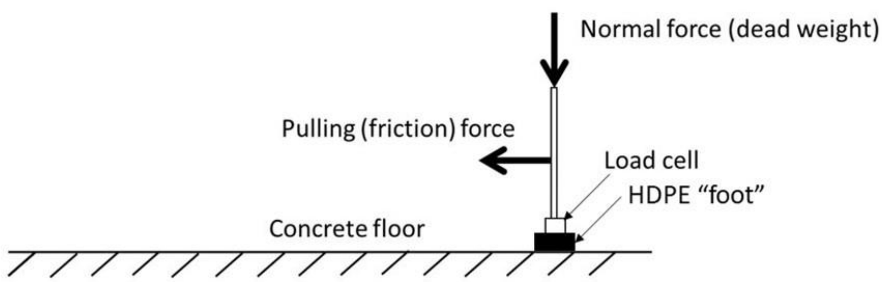

Figure 1. Schematics of surface friction tester (dead weight:10.3 kg; HDPE "foot" was pulled over a 48.25 cm path while a normal load was applied on it).

Tests were conducted after weekly scraping of the floors to remove manure. The floor was tested in four areas according to the observations of sow activities: sleeping, low traffic, high traffic and dunging areas, with details described by Yan et al. (2018). Friction was measured both parallel and perpendicular to the direction of the slats. Parallel tests were run along the slats, while perpendicular tests were run along the 'girder' portions of the slats.

2.2 Air quality and floor cleanliness

Assessment of pen cleanliness and air quality was conducted to provide information on the effect of floor porosity (slat-gap ratio) on manure removal.

2.2.1 Air quality

Ammonia concentration was measured continuously in each room with a Thermo NH_3 17C Analyzer (Thermo Fisher Scientific, Waltham, Massachusetts, USA) set with an averaging time of 300 s (5 min) and connected to a data logger (Model CR 1000, Campbell Scientific, Logan, Utah, USA). The ammonia analyzer was checked weekly with a 10 ppm NH_3 calibration gas and clean air (0 ppm) for possible drift and re-calibrated if necessary. Temperature (T-Type Thermocouples, Honeywell, Charlotte, North Carolina, USA) and relative humidity (Model HIH-4602 sensors, Honeywell) were continuously recorded at three locations in each room with a data logger (Model CR 1000, Campbell Scientific, Logan, Utah, USA) recording at 5 min intervals (Yan et al., 2018).

2.2.2 Floor cleanliness

Pen cleanliness was assessed weekly from time-lapse photographs taken hourly by two cameras (Pentax Optio W80, 5x wide angle zoom (28-140 mm); Pentax Ricoh Imaging Americas Corporation, Denver, CO) during the 12 h of 'lights-on' (07:00 h -19:00 h) on the day preceding floors being scraped to remove any manure build-up. The time-lapse pictures were analyzed using an image processing software MIPARTM (Sosa et al., 2014) to calculate the percent of floor area covered by manure (Yan et al., 2018). The floor was divided into the same four areas as previously for analysis: sleeping, low traffic, high traffic and dunging areas. A rectangle on the floor surface of each area was cropped out of each time-lapse photo and set to grayscale color. The "adaptive threshold" function in MIPAR™ was then applied to distinguish manured floor area from clean floor area as the manured area was presented as red color. The gaps between the slats could be misidentified as the manured area because their color was close to black. As a result, those gaps which were not blocked by manure were removed from each image manually through "manual edit function". After that the percentage of floor area covered by manure were defined by using "area fraction" function in "measurement" section of MIPAR™. Eventually the percentage of manured area of the whole floor, in other words, floor cleanliness was calculated by averaging the four area fractions.

2.3 Animals tested

Fifty nulliparous Yorkshire × Large White gilts (Genesus, Inc.) were artificially inseminated at second post-pubertal estrus. After pregnancy confirmation at 5 weeks of gestation, animals were moved to the Control (n = 24) and Test (n = 25) rooms. Sows remained in the gestation pens until 15 weeks of gestation when they were transferred to farrowing rooms. After lactation, insemination and pregnancy confirmation they were transferred for the second gestation (n = 22 and 21, for Control and Test sows, respectively) to the same floor treatment at 5 weeks of gestation. Sows were removed from the trial during gestation only if ill or an injury prevented them from effective social interaction and/or accessing feed. Notable lameness (≥ score 2, see 2.4.1.) was treated with analgesic (Anafen, Boehringer-Ingleheim) according to the required barn protocol and recorded. Treatment was not to occur within 48 h of scheduled gait scoring, if possible. Sows were fed individually 2.3 to 2.7 kg/day of a commercial gestation diet (12.28 MJ /kg ME, 13.5 % CP,) according to body condition and stage of pregnancy, to meet their nutritional requirements for maintenance and foetal growth according to the NRC (2012). Animals were cared for in accordance with the Canadian recommended code of practice (National Farm Animal Care Council, 2014) and the experimental animal use protocol (F14-013) was approved by the institutional animal care committee of the University of Manitoba (Winnipeg, MB, Canada), in compliance with the Canadian Council on Animal Care guidelines (Canadian Council on Animal Care, 2009).

2.4 Measurements on animals

Reproductive performance was assessed in terms of number of piglets (total born, born alive, stillborn, weaned), piglets' weight at birth and weaning (3 weeks of age) and weaning to estrus interval. Sow body weight and back fat were measured at 5 and 15 weeks of each gestation and at weaning.

2.4.1 Sow cleanliness

From time-lapse photographs (Pentax Optio W80, 5× wide angle zoom (28-140 mm); Pentax Ricoh Imaging Americas Corporation, Denver, CO), the cleanliness of animals was analyzed using MIPAR™ (Sosa et al., 2014) as the percentage of body area "stained" by manure (Yan at al. 2018). The strips painted on the back of sow in different colors were removed manually because they could be misidentified as contaminated area. Four anatomical areas of each sow:

rear, back and both flanks were evaluated (Figure 2). The total percentage of manure-stained area of a sow's body was determined by averaging the four area fractions. Since cleanliness of animals could be influenced by room temperature, air quality and humidity, which varied over the test period, sows' cleanliness in both rooms was assessed on the same days every week from 6 to 15 weeks of gestation.

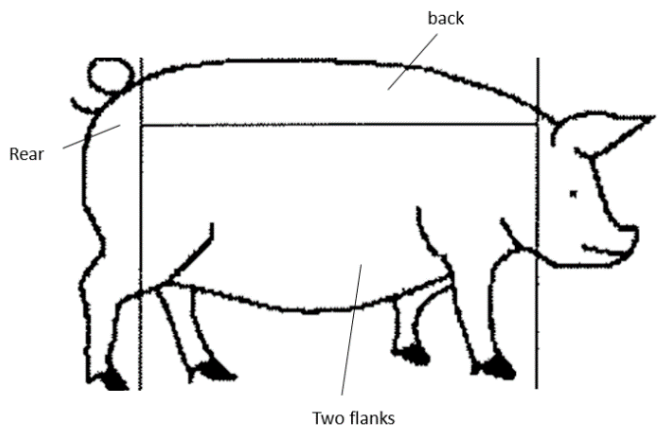

Figure 2. The anatomical areas of sow used for cleanliness evaluation (based on Minvielle and Le Roux, 2009)

2.4.2 Indicators of lameness: Foot lesions and weight distribution

Sows were scored for lameness at 5 and 15 weeks of gestation according to a 5-point gait score adapted from Main et al. (2000) (0: normal gait and even strides; 1: abnormal gait, stiffness, but lameness not easily identified; 2: lameness detected, shortened strides, sow puts less weight or avoids putting weight on one leg; 3: sow does not bear weight on one leg; 4: non-ambulatory).

Claw lesions were observed at 6 weeks of gestation and within one week after farrowing (designated as week 17). On week 6 of gestation, sows were confined in a chute (Feet First® chute, Zinpro Corporation, Eden Prairie, MN), their feet were washed with water and pictures of each foot were taken with a digital camera (PowerShot SX50HS, Canon Canada Inc., Mississauga, ON, Canada) from the left and right sides and from the underside. After farrowing, pictures of each foot were taken from the left and right sides while the sow was standing in the farrowing crate and from the underside while the sow was lying. Four types of feet lesions were scored by one observer blinded to treatments using a 4-point severity scale (Table 1) adapted from the FeetFirst® Lesion Scoring Guide (Zinpro Corporation, Eden Prairie, MN, USA). The intra-observer agreement was 94%.

Table 1. Feet lesions scoring grid for four types of lesions scored with a 4-point severity scale adapted from the FeetFirst® Lesion Scoring Guide (Zinpro Corporation, Eden Prairie, MN, USA).

Severity	Toes and Dew claws Length	Toes Wall cracks	Underside, Heel overgrowth and erosion	Underside, White line and heel-sole cracks
0 Normal	**Normal** length of all Toes and Dew claws	**No** crack in toe wall *(Vertical or horizontal)* or hemorrhage evident.	**No** overgrowth or erosion of soft heel tissue.	**No** separation at the juncture heel-sole or along white line
1 Mild	At least one Toe or Dew claw **slightly longer** than normal *(25 to 50% longer)*	**Short/shallow** crack in toe wall *(Vertical or horizontal)* and/or hemorrhage evident	**Slight** overgrowth and/or erosion of soft heel tissue.	**Slight/short/shallow** separation at the juncture heel-sole or/and along white line
2 Moderate	At least one Toe or Dew claw **significantly longer** than normal (*50 to 100% longer)*	**Long but shallow** crack in toe wall *(Vertical or horizontal).*	**Numerous** cracks with **obvious** overgrowth and erosion of soft heel tissue.	**Long** and **shallow** separation at the juncture heel-sole or/and along white line.
3 Severe	**Very Long** Toes *that affect gait when walking (more than two time regular length)* or at least one dew claw **torn**, partially or completely missing.	**Multiple** *(more than 3)* or **deep** crack in toe wall *(Vertical or horizontal).*	**Large amount** of erosion and overgrowth with cracks throughout.	**Long** and **deep** separation at the juncture heel-sole or/and along white line

On weeks 6 and 14 of gestation, weight distribution was assessed using a force plate according to a previously described method (Conte et al., 2014). The force plate (Pacific Industrial Scale Co. Ltd., Richmond, BC, Canada) consisted of four individual stainless-steel platforms (front:101.6 × 30.5 cm^2, rear:111.8 × 30.5 cm^2), each resting on four cantilevered-beam load cells. A feeder was included on the front gate to draw the sow's attention towards a standardized direction. The total weight and the weight placed on each platform (14 data per second) were recorded and saved using the Pacweight Animal Weight custom software (Pacific Industrial Scale Co. Ltd., Richmond, BC, Canada). The position of the sow's legs and head was recorded using one

DFK22AUC03 camera (The Imaging Source Europe GmbH, Bremen, Germany) with lens (Pentax CCTV C418DX, 4.8 mm, 1:1.8; Pentax Ricoh Imaging Americas Corporation, Denver, CO) and the IC Imaging Capture 2.2 software (The Imaging Source Europe GmbH) synchronized with the Pacweight Animal Weight custom software. Sows were measured for a period of 15 min, but based on video recordings, only periods when the sow stood with her head in the feeder and her feet over the correct platform were kept. Moreover, any body weight per reading higher or lower than 5% of the average body weight of the sow was eliminated as previously described (Conte et al., 2014). For each leg, the average percentage of weight (% BW) and its standard deviation (SD) was calculated. The average ratio of lower to higher weight applied by contralateral legs was calculated separately for fore and hind legs (contralateral ratio). Weight shifting (WS) was evaluated according to the same method previously described (Conte et al., 2014) and frequency of WS per min, percentage of time WS and amplitude of WS (in % of BW) were calculated.

2.4.3 Behaviour

Postural behaviour (time budget of standing, lying, sitting and frequency of posture changes) was measured using accelerometers according to a previously developed method (Ringgenberg et al., 2010), twice per gestation on weeks 6 and 14. Two accelerometers (Hobo Pendants G Data Logger, Onset Computer Corporation, Pocasset, MA, USA), safely protected inside a Velcros-pocket and a Vetrap™ 3M™ covering, were placed on the front and hind left legs. The device recorded the acceleration in the vertical direction (the x-axis) every second, for 18h from 05:00 h. Data from recordings were read using the Hoboware Pro software (Onset Computer Corporation, Pocasset, MA, USA). A leg was considered in the vertical position if the x-axis acceleration was higher than 0.59 g (Ringgenberg et al., 2010). The sow was considered standing if both legs were in vertical position, sitting if the front leg was in vertical position and the hind leg was not, and lying otherwise. Frequency and duration of bouts for each posture (standing, sitting, lying) were calculated. Thereafter, percentage of time spent in each posture and frequency of changes between posture were calculated.

Sows' behaviour was also video recorded by camcorder (Canon Vixia HF R52, 57× advanced zoom; Canon Canada Inc., Brampton, ON) three times per gestation on weeks 6, 10 and 14 to assess time budget of activities for 10h during daylight from 08:00 h according to the ethogram presented in Table 2. Video recordings were watched by one observer blinded to treatments and scan sampling at 6 minutes interval was used to determine percentage of time spent performing each of the behaviours observed. Intra-observer agreement was 89%.

Table 2. Ethogram of the behaviours observed on weeks 6, 10 and 14 of gestation for 10 h period during daylight

Behaviour	**Definition**
Walking	Taking more than one step or changes posture
Exploring	Performing any oral or nasal behaviour (e.g. sniffing, nosing) directed to something in the pen where the animal is housed such as the walls, feeder or floor
Feeding	Consuming food or water
Social interaction	Performing any oral or nasal behaviour (e.g. sniffing, nosing, pawing) directed to the body of another animal in the pen. Being involved in aggressive behaviour (e.g. biting or aggressive head knocks) with another animal
Passive	Sitting or standing without performing any activity
Resting	Lying down without performing any activity
Other	Any other behaviour (e.g. eliminative behaviour)

2.5 Statistical analyses

Performance, lameness and behaviour variables were analyzed for the effects of the treatment (Control vs Test) and gestation number (first vs second) for each week of gestation separately using the SAS software (version 9.3; SAS Inst. Inc., Cary, NC) with the gilt (or sow) as the experimental unit. The MIXED procedure was used with floor treatment as a fixed effect, gestation number as a repeated measure and their interaction in the model. When interaction was significant, the effect of floor treatment within each gestation (slice effect) was tested. For feet lesions scores and weight distribution, data were averaged and analyzed per pair of front and rear limbs separately. For gait score, sows were categorized as sound (score = 0) or lame (score ≥ 1) and analyzed using a logistic regression analysis (PROC LOGISTIC). For sow and floor cleanliness, as well as air quality, the mean values and standard deviations were calculated by univariate analysis in SAS, and variance analysis was performed to compare the Test and Control floors. A probability level of $P \leq 0.05$ was chosen as the limit for statistical significance in all tests. Probability levels of $P \leq 0.10$ were considered as a tendency. Data in text and tables are presented as least squares means ± SEM, unless indicated otherwise.

3. Results

3.1 Room and floor characteristics

3.1.1 Floor friction

The measured dynamic coefficient of friction (DCOF) for HDPE on new (dry) floor was 0.36, with a standard deviation of 0.06. The DCOF decreased sharply within the first week of occupancy by animals in both rooms, specifically from 0.36 to 0.17 for the Test floor and from 0.36 to 0.15 for the Control, respectively. No significant reduction in DCOF was observed after the first week of use. At the end of the 2 gestation cycles, the DCOF was 0.24 and 0.23 for the Test and Control floors, respectively, and there was no significant difference ($P>0.05$) in DCOF between the two treatments. The DCOF at the end was higher than after the first week of occupancy. There was dry manure remaining on the dunging and high traffic areas even though the floors were scraped before friction test, which could possibly increase friction.

3.1.2 Indoor air quality

There was no significant ($P>0.05$) difference in the temperatures between the two test rooms during two gestations (Table 3). Because the first gestation occurred in summer to autumn time (from June to October) with average outdoor temperature around 20 °C and the second gestation in winter time (from November to February) with average temperature about -20 °C, the room temperature for the first gestation was higher with greater variation than during the second. There was no significant ($P>0.05$) difference in relative humidity between the two rooms (Table 3).

Table 3. Average values and standard deviations of measured ammonia concentration, temperature and relative humidity in the two sow gestation rooms** with different slat to gap ratios of slatted concrete floor.

Floor	Ammonia (ppm)		Temperature (℃)		Relative Humidity (%)	
	Mean	SD	Mean	SD	Mean	SD
1st Gestation						
Test floor	0.3	0.2	23.4	3.1	67.8	11.1
Control floor	0.4	0.3	22.4	3.0	66.8	11.5
2nd Gestation						
Test Floor	2.5	1.1	18.2	0.7	70.0	4.1
Control Floor	2.5	1.0	18.9	0.6	64.7	6.3

** Test floor = 105 mm slats, 19 mm gaps; Control floor = 125 mm slats, 25 mm gaps. 1st Gestation was during summer and autumn. 2nd Gestation was during winter conditions.

The ammonia concentration fluctuated from morning to night every day, and was higher in winter (2nd gestation) than the summer period, but the differences in ammonia concentration between the two rooms were negligible (P>0.05). In other words, the two slatted floor designs did not result in any significant difference in ammonia concentration in the rooms.

3.1.3 Floor cleanliness

The average percentages (±SD) of manured floor area in the first gestation were 53.1±8.5% and 51.0±9.1% on the Test and Control floors, respectively; the corresponding values were 51.3±6.1% and 55.8±5.2% for the second gestation. Total floor area covered with manure for each gestation did not differ significantly between floors (P>0.05; Figure 3). Statistical analysis showed that there were no significant differences in the percentage of manured floor area between the Test and Control floors for the different areas during both gestation periods (P>0.05; Table 4). Manure-coverage was the lowest for the sleeping area (≤ 30%) and the highest for the dunging area (> 70%). On some occasions, the high traffic area appeared to have more manure coverage than dunging areas. A close examination revealed that the high traffic area was close to the waterers, so some of the wet area was from drinking water rather than from urine.

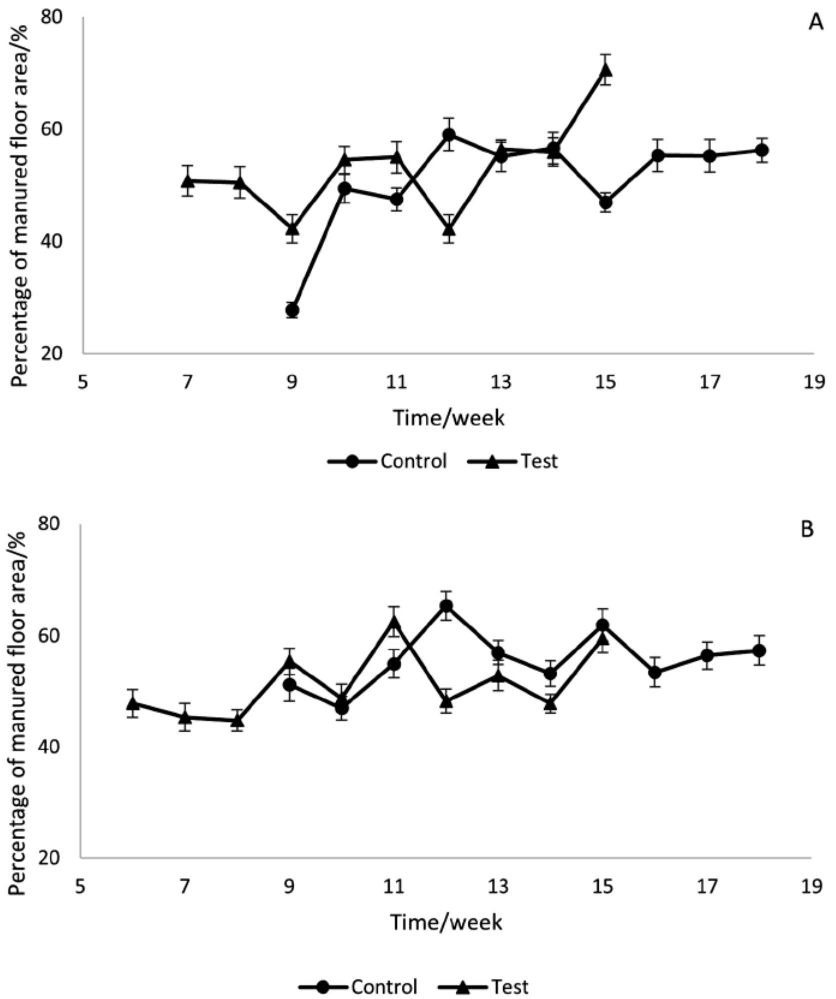

Figure 3. Comparison of percentage of manured floor on total area between two rooms (A: Gestation 1; B: Gestation 2). The test for Test floor started 3 weeks later than Control in both gestations due to normal barn flow. For the purpose of using the same timeline, the plot of Test floor was drawn 3 weeks later than Control.

Table 4. Average percentage of manure soiled area on slatted floor in two sow gestation rooms with different slat to gap ratios** of slatted concrete floor.

Floor	Average percentage of manured floor area (%)									
	Total		Sleeping		Low Traffic		High Traffic		Dunging	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1st Gestation										
Test floor	53.1	8.50	21.8	7.9	34.4	13.0	73.70	12.0	82.7	8.4
Control floor	51.0	9.12	18.7	6.9	36.1	11.5	71.8	16.4	77.1	11.5
2nd Gestation										
Test floor	51.3	6.1	23.7	6.4	47.8	8.1	61.7	8.5	72.2	12.6
Control floor	55.8	5.2	30.4	12.5	45.4	12.9	72.0	6.7	75.5	5.0

** Test floor = 105 mm slats, 19 mm gaps; Control floor = 125 mm slats, 25 mm gaps. 1st Gestation was during summer and autumn. 2nd Gestation was during winter conditions.

3.2 Measurements on animals

Several parameters were recorded and analyzed to determine the impact of gestation-flooring treatment on performances (body weight, back fat, reproductive performance), development of lameness (feet lesions, weight distribution), activities and postural behaviour, and body cleanliness. Overall, the treatment affected some variables measured (feet lesions, limb-weight distribution) but no large and generalized effects were observed across the different dimensions studied.

3.2.1 Sow cleanliness

The variations in percent body surface soiled by manure followed the same pattern in the two rooms (Figure 4). The mean percentage of manured body area was similar in both treatments and gestation cycles (gestation 1: 27.1% and 26.9%, for Test and Control floors respectively; gestation 2: 27.0% and 26.9%, for Test and Control, respectively). There was a peak in weeks 10 to 12 in the first gestation, associated with higher ambient temperatures in those weeks.

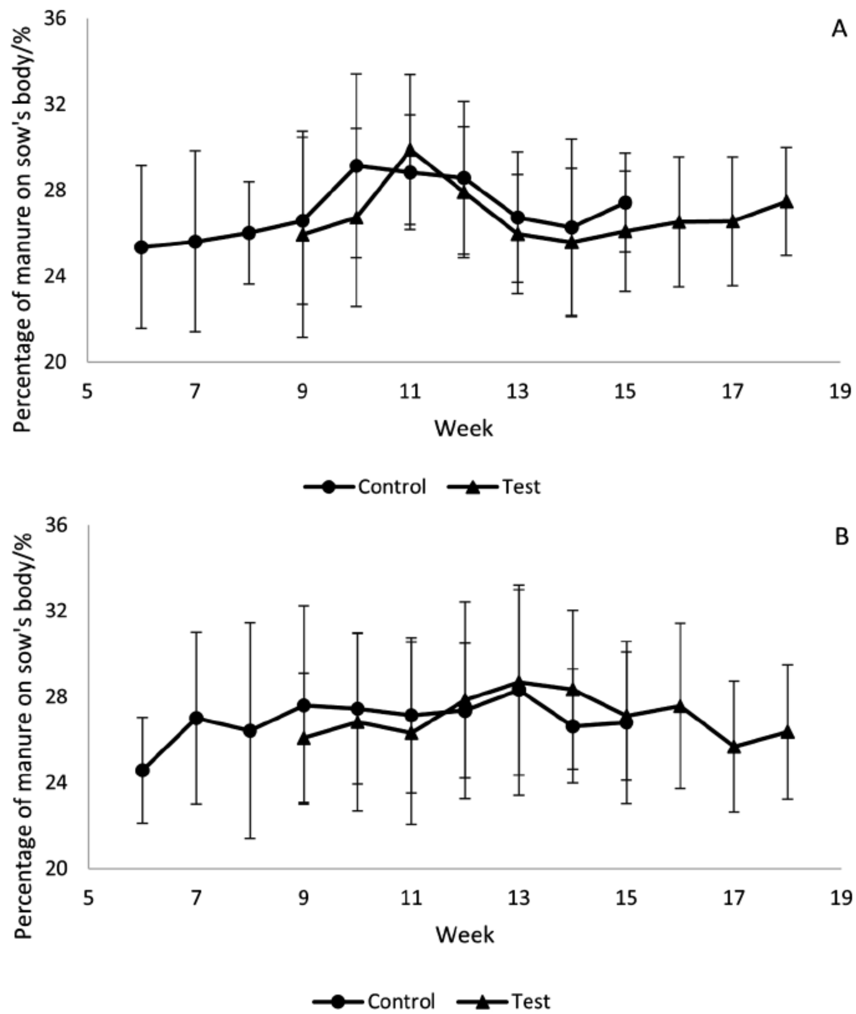

Figure 4. Comparison of percentage of sow's body surface soiled by manure between two rooms (A: Gestation 1; B: Gestation 2). For the purpose of using the same timeline, the plot of Test floor was drawn 3 weeks later than Control

3.2.2 Performance

Sow body weight logically increased during gestations and was higher in second gestation (Table 5). While weight gain during the first gestation was higher in Test sows than Control sows (42 kg vs 35 kg, Test vs Control, respectively; P=0.009), the effect was reversed in the second gestation (P=0.018). However, back fat was unaffected by treatment. Reproductive performance also differed between gestations with more piglets born and born alive, and a higher litter birth weight after the second gestation. Floor treatment had an effect on the litter weight at weaning (84.7 vs 77.4 ± 2.0 kg, for Control and Test sows respectively; P=0.015), most likely due to a tendency for a larger litter size at weaning in Control sows (12.2 vs 11.5 ± 0.3 piglets, for Control and Test sows respectively; P=0.092).

Table 5. Effects of floor treatment and gestation number on performance and behaviour (least square means)

Measure	Week of gestation	Control floor*		Test floor*		SEM max	Effects (*P*-value)		
		1st gestat-ion	2nd gestat-ion	1st gestat-ion	2nd gestat-ion		Floor	Gestat-ion	Inter-action
Performances									
Sow body weight	5	181	211	177	216	1.7	0.67	0.0001	0.002
(kg)	15	216	242	219	242	2.6	0.48	0.0001	0.50
Number of piglets									
Total born		14.5	15.0	13.7	16.3	0.6	0.71	0.010	0.065
Born alive		13.6	14.5	12.8	14.9	0.6	0.74	0.017	0.32
Weaned		11.5	12.9	11.1	12.0	0.5	0.092	0.030	0.61
Litter weight (kg)									
At birth		19.0	23.8	18.2	23.5	0.8	0.52	0.0001	0.72
At weaning		82.8	86.6	74.8	80.0	3.1	0.015	0.12	0.81
Activities (% of time)									
Walking	10	3.48	3.12	2.89	4.69	0.48	0.35	0.061	0.006
Passive	10	4.65	6.74	3.17	4.33	0.79	0.006	0.012	0.46
Feeding	10	5.09	3.83	2.44	4.60	0.50	0.081	0.26	0.0001
Social interaction	14	4.09	1.17	2.67	3.74	0.45	0.49	0.087	0.0001
Postural Behaviour (% of time)									
Lying	6	78.3	75.0	83.3	72.6	1.9	0.47	0.0001	0.009
	14	77.8	81.1	75.1	77.9	2.1	0.19	0.040	0.88
Sitting	6	5.4	4.9	4.5	5.1	0.8	0.66	0.90	0.42
	14	6.3	2.4	5.2	4.8	1.5	0.63	0.015	0.049
Standing	6	16.3	20.0	12.2	22.5	1.8	0.62	0.0001	0.021
	14	15.8	16.3	19.6	17.1	1.9	0.26	0.49	0.29
Frequency of posture changes									
Lying to sitting	14	22.2	14.4	17.7	19.4	2.2	0.92	0.016	0.0002
Lying to standing	14	1.1	3.3	2.7	3.6	0.9	0.27	0.039	0.35
Sitting to standing	14	11.7	8.0	9.5	11.7	1.3	0.56	0.50	0.016
Sitting to lying	14	12.1	8.4	10.3	10.6	2.0	0.94	0.24	0.15
Standing to lying	14	11.1	9.3	10.1	12.3	1.2	0.45	0.86	0.051

Standing to sitting	14	1.7	2.0	2.1	3.1	1.1	0.44	0.39	0.66

* Control floor: 125 mm slats and 25 mm gaps; Test floor: 105 mm slats and 19 mm gaps

3.2.3 Lameness

Incidence of lameness, measured as gait scores > 0, was similar for sows in both treatments for both gestations (14.4 vs 16.7 %, for Control and Test sows respectively; P > 0.1). No sow was scored 4 and sows were scored 3 in only two instances. Two sows on Test floor were removed from the trial due to injury-induced lameness in gestation 1 and one in gestation 2 due to a knee abscess. While only two Control sows were removed from the trial in gestation 2 due to lameness, a total of 11 sows were treated with analgesics, 5 in each gestation and 1 in both gestations before being removed in gestation 2 with a severe wall crack. Only 1 Test sow required analgesic treatment, but was not removed. Two sows in Control and one in Test flooring group were not bred within the required breeding period and were not part of the gestation 2 group. One bred Test sow was not pregnant and not part of the gestation 2 group.

Considering feet lesions, all feet from all sows had a score of 1 or more at least once during the experiment for heel overgrowth and erosion (HOE), white line and heel-sole cracks (WHC) and wall cracks (WC). Considering moderate to severe lesions only (score 2 and 3), occurrence dropped down to 52 and 63% of feet for WC, but remained at 96 and 100% for both HOE and WHC when comparing Test and Control sows, respectively. However, only 12% of sows in both treatments had feet with a score of 1 or more for length of toes and dew claws. When considering the average scores, some effects of the floor treatment were observed on the severity of HOE and WC (Table 6). The severity of HOE was higher for front (P<0.001) and rear (P<0.001) feet in Control sows than Test sows in both gestations. Lesion score for WC was also higher for rear feet in Control sows compared to Test sows in both gestations (P=0.003). However, some of these effects were already present as soon as week 6 of the first gestation, i.e. only one week after the sows moved to the gestation group-housing, with higher scores in Control than Test sows for HOE score for both front and rear feet (P=0.02 and P=0.0004, respectively) and for WC score for rear limbs (P=0.009). It is therefore difficult to discern treatment effects from pre-existing conditions, even though the gilt groups were on similar flooring (partially slatted; 125 mm slats and 25 mm gaps) before moving to the treatment pens. Toes and dew-claws lengths and white line and heel-sole cracks were not affected by the floor treatment. In general, feet lesions scores for HOE and WLC increased during gestation and decreased during lactation and rebreeding when sows were on different flooring. The WC score remained similar or increased slightly during the same period.

Analysis of weight distribution showed significant effects of floor treatment and gestation number on several variables measured on hind legs (Table 6) but fewer effects for most variables recorded on front limbs. Considering both gestations, Control sows, compared to Test sows, spent more time weight-shifting in late gestation (37.1 vs 32.3 ± 1.6% of time, P=0.036, respectively), had a lower ratio between the weights applied by contralateral hind legs in early (0.74 vs 0.78 ± 0.01, P=0.015, respectively) and late gestation (0.77 vs 0.80 ± 0.01, P=0.066, respectively), had a higher variability (SD) of the percentage of weight applied on hind limbs in early (SD = 4.3 vs 3.9 ± 0.10, P=0.006, respectively) and late gestation (SD = 3.9 vs 3.4 ± 0.12, P=0.003, respectively), for an overall average of 21.4% of body weight applied on each hind leg. Finally a higher amplitude of weight shifting was measured in Control sows on front legs in early gestation (6.62 vs 6.19 ± 0.13, P=0.028, respectively) and on hind legs in late gestation (6.94 vs 6.14 ± 0.15, P=0.0004, respectively) compared to Test sows (Table 6) across both gestations.

Table 6. Effects of floor treatment and gestation number on feet lesions scores and weight distribution (least square means)

Measure	Week of gestation	Control floor*		Test floor*		SEM max	Effects (*P*-value)		
		1st gestat-ion	2nd gestat-ion	1st gestat-ion	2nd gestat-ion		Floor	Gestat-ion	Inter-action
Feet lesions									
Heel overgrowth and erosion score									
Front feet	6	1.96	1.86	1.58	1.83	0.12	0.072	0.45	0.081
	17	2.48	2.11	1.97	1.93	0.09	0.0003	0.062	0.19
Rear feet	6	2.22	2.28	1.76	2.13	0.10	0.003	0.007	0.051
	17	2.73	2.52	2.21	2.35	0.09	0.0003	0.73	0.066
White line and heel-sole cracks score									
Front feet	6	1.73	1.74	1.64	1.75	0.12	0.73	0.57	0.63
	17	2.19	1.95	2.02	2.18	2.00	0.75	0.66	0.050
Rear feet	6	1.65	1.82	1.64	1.94	0.11	0.59	0.011	0.42
	17	2.06	2.01	2.07	2.30	0.11	0.18	0.37	0.15
Wall cracks score									

Front feet	6	1.00	1.33	1.06	1.35	0.10	0.63	0.0003	0.79
	17	1.23	1.67	1.36	1.48	0.13	0.79	0.009	0.12
Rear feet	6	1.22	1.69	0.98	1.37	0.11	0.003	0.0001	0.68
	17	1.54	1.68	1.30	1.52	0.12	0.069	0.084	0.65
Weight distribution									
Standard Deviation of percentage of weight applied (% body weight)									
Rear feet	6	4.08	4.57	3.76	4.10	0.15	0.006	0.007	0.62
	14	3.83	3.97	3.18	3.57	0.16	0.003	0.023	0.28
Ratio of weight applied between contralateral limbs									
Rear feet	6	0.740	0.737	0.793	0.765	0.018	0.015	0.25	0.35
	14	0.753	0.782	0.796	0.803	0.017	0.066	0.11	0.33
Percentage of time weight shifting (%)									
Rear feet	6	39.6	45.0	36.7	42.3	1.7	0.072	0.002	0.97
	14	38.3	35.9	30.3	34.3	1.9	0.036	0.58	0.024
Amplitude of weight shifting (% bodyweight)									
Front feet	6	6.46	6.77	6.14	6.23	0.20	0.028	0.24	0.51
	14	6.27	6.27	5.76	6.22	0.24	0.26	0.22	0.23
Rear feet	6	6.94	7.56	6.81	6.94	0.21	0.083	0.051	0.20
	14	6.65	7.22	6.00	6.27	0.19	0.0004	0.016	0.38

* Control floor: 125 mm slats and 25 mm gaps; Test floor: 105 mm slats and 19 mm gaps

3.2.4 Behaviour

Most behaviours were affected by gestation number with sows being generally more active in second than in first gestation on week 6 (Resting: 53.7 vs 71.9 ± 2.3%, P=0.0001, respectively) and week 10 (Resting: 57.9 vs 73.1 ± 2.0%, P=0.0001, respectively). Only activities significantly affected by the floor treatment are reported in Table 5. Observation of time budget of activities showed a significant effect of floor treatment on passive behaviour at week 10 with Control sows spending more time passive than Test sows (5.7 vs 3.7 ± 0.5%, P=0.006, respectively) for both gestations. Some interactive effects of treatment and gestation number were also observed in the middle (week 10) and end (week 14) of gestation. Control sows spent more time in social interactions than Test sows at the end of the first gestation (4.1 vs 2.7, P=0.029) but less at the end of second gestation (1.2 vs. 3.7%, P=0.0006). At week 10 of gestation, Control sows spent more time feeding in first gestation only (5.1 vs 2.4%, P=0.0001, respectively) and less time walking in second gestation only (3.1 vs 4.7%, P=0.026, respectively) than Test sows.

Looking at postural behaviour, only interactive effects of treatment and gestation number were seen (Table 5). At week 6 of their first gestation, Control sows spent more time standing (16.3 vs 12.2% ± 1.3, P=0.028, respectively) and less time lying (78.3 vs 83.3% ± 1.2, P=0.005, respectively) than Test sows. At week 14 of second gestation, Control sows spent less time sitting than Test sows (2.4 vs 4.8% ± 0.9, P=0.049, respectively). Finally, no major effect of treatment was observed on the frequencies of posture changes (Table 5) and significant interactions observed for week 14 of gestation did not translate into significant differences between floor treatments in either gestation.

4. Discussion

The use of total or partially slatted concrete flooring for group-housed sows, which predominates in many countries, presents challenges for sow welfare and longevity. The risk of lameness, alone, is double that of housing on solid concrete floors (Heinonen et al, 2006) and more than four times greater than on solid flours with deep bedding (Kilbride et al., 2009a). In the present study, no difference on the incidence of lameness was observed between treatments. Apart from the abrasiveness and hardness of concrete, slipping and claws wedging in the gaps between slats (Mouttotou et al.,1999) as well as chipped, sharp or worn slat edges (Kilbride et al., 2009b) of concrete floors are particular challenges that can cause uneven pressure distribution, claw lesions and lameness. It has been reported that first parity gilts represent up to 50% of sows culled for feet and leg problems (Rapp, 2010). Heel overgrowth and erosion and white line lesions can be noted in rear feet of young gilts and increase with age (Rapp, 2010) and their prevalence was higher than 90% in the present study. In general, claw lesions were reported present in 60 – 95% of sows (Pluym et al., 2011; Kilbride et al., 2009a). Heel overgrowth is the most common issue and results from standing and walking on hard surfaces like concrete (Rapp, 2010); it was the feet lesion with the highest severity scores in the present study. The overgrowth can place increased pressure on claw sidewalls resulting in cracks in the wall and along the white line. Such lesions and erosion, if they reach the underlying corium, are usually painful and result in lameness.

North America has no dimensional requirements for slatted flooring although slats widths of 127 mm separated by gaps/voids of 25 mm are most common and considered best for manure removal to an underfloor pit. While the European Union does require a minimum slat width of 80 mm and a maximum gap width of 20 mm (Council of the European Union, 2008), the scientific basis for these values is not readily available. The goal of the current study was to determine the best slat and gap width to use for ease of sow movement and comfort while not compromising manure removal. From the first phase of the study, using kinematic analysis of gilts and sows walking along a test corridor, gait was least affected by a combination of narrower slat and gap widths of perpendicular-oriented slats (Devillers et al., 2019). The gait of larger and lame sows was less affected by the slat and gap widths tested than were smaller sows and gilts. It is the smaller-footed animals, nulliparous and first parity sows, that are more vulnerable to getting claws caught in gaps and are most likely to be culled for lameness (Anil et al., 2007). Therefore, this study started with pregnant gilts and followed them through two consecutive gestations in pens equipped with the Test floor or the Control floor. Both pen floors were newly manufactured to specification. The dynamic coefficient of friction of the two pen floors was found to be 0.36 when they were dry and new, which was close to the results of Nilsson (1988) that the DCOF of dry clean concrete to be between 0.35 and 0.38 at a normal load of 500 and 900 N, respectively. The DCOF reduced sharply within the first week of occupancy by animals. This could be attributed to the physical contact between pig claw/body and concrete floor, or the mechanical abrasion from weekly scraping before test. It meant the floor soiled with manure could be too slippery for pigs and potentially cause lameness (McKee and Dumelow, 1995). However, this did not appear to be the case from observations and video recordings. Slip usually happens from an inability to adapt to the floor conditions (Hanson et al., 1999). In this case, pigs most likely altered their gait, i.e., shortening stride length and reducing walking speed. The DCOF derived in this study was from measurements taken between HDPE and concrete floor, which still differs from live pig claw on concrete floor. The live claw would probably be less influenced by the wet floor due to animal adaptability (Phillips & Morris, 2000).

The incidence of actual lameness was not different between the floor types but amounted to about 15% for both treatments which is comparable to previous studies (Heinonen et al. 2013). On the other hand, there were differences between treatments in some of the claw health and behaviour indicators. Sows on the Control floor had higher HOE scores on rear feet by the end of the first gestation and on both front and rear throughout second gestation. Similarly, WC scores were greater in rear feet of sows on Control floor in both gestations. However, WLC scores increased similarly in both treatment groups in both gestations. While severity of HOE and WLC scores tended to decrease during the time sows were on another flooring during lactation and rebreeding, WC scores remained similar or increased on both front and rear claws from week 14 measurements in gestation 1 to the week 6 measurements in the second gestation. This suggests that these WC become more severe over time with increasing potential to affect underlying living tissue causing pain. The rear feet of sows on Test floor had a lower WC severity score and demonstrated less weight shifting, particularly towards the end of gestation when weight-bearing would be greatest. As well, only 1 Test sow, but over 20% of Control sows showed lameness of sufficient severity to require treatment with analgesic during gestation. These are indicators that the narrower slat and gaps of the Test floor offered some benefits to sow foot health and comfort. However, it is difficult to be certain of the overall impact of the Control floor on HOE since sows on Control floor tended to have higher HOE score than Test floor sows after the first week on the floor. Neither Test nor Control sows' claws were scored before they entered the study pens, but, both groups were housed on similar partially slatted floors prior to entering the test pens.

Beyond feet lesions and weight distribution, floor treatments had very few effects on the other parameters measured. Performances and behaviour were marginally affected with only a trend for Control sows to be more inactive and walk less than Test sows which would be consistent with a higher discomfort due to more severe feet lesions. However, it did not translate into more time spent lying or a reduced frequency of posture changes. Gait scores were not different between treatments either. Lameness usually affects postural behaviour with longer time spent lying (Enokida et al., 2011) and more difficulty changing posture (Roca et al., 2016). Therefore, the level of discomfort induced by the more severe lesion scores observed in Control sows was most likely not intense enough to modify significantly sows' behaviour or translate into clinical signs of overt lameness, during the study period. Further tests at the commercial level on a larger number of animals would be needed to confirm the impact of smaller gaps on feet lesions and potentially on lameness.

Finally, floor treatment had no effect on air quality and cleanliness of both floors and sows. These results agree with observations of Aarnink et al. (1997) who did not find any significant difference in ammonia emission and wetted surface of the slats after urination for concrete floor with 100 mm slat and 20 mm gap compared to concrete floor with 70 mm slat and 18 mm gap. Compared to the results of Ni et al. (2000) that the average daily ammonia level at a mechanically ventilated hog barn was 5.6±0.41 ppm, our average ammonia concentration (2.5 ppm in Gestation 2 during winter conditions) was very low. The low ammonia level in this study were partially attributed to the large rooms used in the experiment. Specifically, each room had two pens, but only one pen was used for testing. In other words, there was twice as much space for ammonia to "dilute" in the test room compared with a fully stocked room. Aarnink et al. (1997) also found the mean area of solid floor wetted with urine was 0.07 m^2 per pig for the concrete slatted floor with 100 mm slat and 20 mm gap. According to the floor size and animal occupation provided in their paper, 54% area was wetted by urine, which agrees well with the results in this paper (53% in gestation 1 and 51% in gestation 2 on Test floor with 105 mm slat and 19 mm gap). The manured body area of sows was around 27% for both floors, which we can consider the sows were rather clean. Minvielle and Le Roux (2009) assessed pig cleanliness using a five-point scale (score 0 to 4) and observed that 40% of pigs' surfaces were assessed as score 3 or 4, but pigs can be considered relatively clean.

Therefore, at the space allowance used in the current study, and despite a slightly lower permeability of 15% for Test floor compared to Control floor (17%), Test floor was as efficient as Control floor for manure removal.

5. Conclusions

As a general conclusion, effects of treatment that were seen do not indicate a marked difference between the two types of floor tested. Nevertheless, Control floor (125/25 mm) seems to lead to higher feet lesions scores and a higher discomfort while standing according to the measurements from the force plate and the need for analgesic administration. However, these differences did not result in differences in gait and lameness scores during the two gestation periods. The effects on behaviour and reproductive performance were also limited. However, in terms of feet health and sow comfort, these results indicate a benefit of the narrower concrete slat (105 mm) and gap (19mm) flooring, at least for smaller or early parity sows.

Conflict of interest statement

None.

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