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DETECTION, IMPLICATIONS AND RISK FACTORS FOR LAMENESS IN GROUP-HOUSED GESTATING SOWS

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Detection, implications and risk factors for lameness in group-housed gestating
sows

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SUMMARY

Lameness, the most general clinical sign of musculoskeletal problems, is a serious welfare and health problem to sows and a cause of considerable economic loss to pig producers. Since 2013, group-housing of sows is mandatory in the European Union, mainly because of welfare concerns. Yet, the prevalence of lame sows tends to be higher in group-housing. A decline in the prevalence of sow lameness by using proper preventive strategies is necessary to improve animal welfare, enhance farmer's working pleasure and diminish financial loss, all of which may contribute to a more sustainable pig production.

A critical review of the literature on sow lameness (**chapter 1**) revealed that to enable optimal prevention of sow lameness, more research is needed on three main areas. First, lameness detection in sows so far has been based on subjective visual scoring systems characterized by a low sensitivity and high inter-observer variability. More objective, precise and sensitive detection methods based on kinematic and kinetic techniques have been successfully applied in other animal species but not yet in sows. Secondly, awareness of the economic implications is recognized as a potential powerful driver to motivate farmers to take action against lameness. The financial loss related to lameness is partly attributed to the (in)direct effect on reproduction. The indirect effect of lameness on sows' reproductive performance has been studied extensively but inconsistency still exists on the direct impact. Finally, critical for the development of preventive strategies is to identify risk factors for lameness. Although risk factors have been studied in stall-housed sows and finishing pigs, research on the risk factors for group-housed gestating sows is scarce.

The aim of this thesis (**chapter 2**) was to enhance prevention of lameness in group-housed sows through improvement of lameness detection, clarification of the reproductive implications and identification of risk factors.

To improve the detection of lame sows, a system, based on force and visual stance variables derived from balance analysis and image processing respectively, was developed: SowSIS (Sow Stance Information System) (**chapter 3**). The demountable and transportable device is practical for on-farm use and detects lameness in sows while standing. Accuracy of the force stance variables was evaluated using reference masses ranging from 5kg to 175kg. SowSIS

proved to be highly accurate ($R^2 \approx 1$) for measuring weight, irrespective of the position of the mass relative to the load cell and the duration of measurements. To determine precision of the force and visual stance variables, five consecutive measurements with SowSIS were carried out for each of 20 pregnant sows that were scored healthy on visual lameness assessment. A sufficient level of precision (within-animal $CV \leq 15\%$) was shown for both the force and visual stance variables, except for the number and duration of kicks (*i.e.* lifting leg off the ground) and weight shifts. A proof-of-concept study was performed on four healthy and four unilaterally lame sows, matched by age and gestation stage to investigate the impact of lameness on leg weight distribution. All sows were lame on the right hind leg. Weight was removed from the lame leg and was primarily transferred to the contralateral leg. The number of kicks significantly increased for the lame leg (mean of 48 versus 23 times/5min; $P < 0.001$). Lame sows showed a lower leg weight symmetry than non-lame sows between the hind legs (64% versus 93%; $P < 0.05$) and between the right legs (54% versus 76%; $P < 0.05$). It was concluded that SowSIS is practical, accurate and precise in measuring stance variables and that force stance variables are able to distinguish lame from visually healthy sows. Future research should establish the accuracy of visual stance variables and the results of the proof-of-concept study need to be confirmed in a large scale validation study including visual stance variables. To enable classification of sows into lame and healthy ones, an algorithm based on the force and visual stance variables should be developed and validated (**chapter 6**).

To encourage pig producers to control and prevent lameness, the economic implications of lameness need to be elucidated, especially regarding the direct effect on reproduction. To achieve this goal, a total of 491 sows from five commercial herds were followed-up to investigate the impact of lameness and claw lesions throughout one reproductive cycle on the reproductive performance of sows (**chapter 4**). No significant associations were found between lameness and sows' breeding performance (*i.e.* weaning-to-oestrus interval and presence of sows not showing oestrus post-weaning, returning to service and aborting). The impact of lameness on the sows' farrowing performance was restricted to an effect on the presence of mummified foetuses. Lame sows were 2.4 times (95% CI: 1.19 – 4.75; $P = 0.014$) more likely to have mummified foetuses. Claw lesions did have an effect on farrowing performance. Sows with white line lesions and skin lesions above the claw respectively, were 1.9 times (95% CI: 1.04 – 3.51; $P = 0.036$) and 4.1 times (95% CI: 1.23 – 13.8; $P = 0.021$) more likely to have stillborn piglets. Twenty-two per cent of all sows left the group throughout the study and almost half of these sows were culled or euthanized. Lameness was

the second most important reason for culling. Sows culled due to lameness were significantly younger compared to sows culled for other reasons (parity: 2.6 ± 1.3 versus 4.0 ± 1.8). In conclusion, lameness mainly affects reproduction indirectly, through the increased culling rate of young sows. The overall herd performance is rather affected than the reproductive performance of an individual sow and the economic implication of sow lameness is thus largely determined by the effect on sow longevity.

Knowledge on the stage in the reproductive cycle at which lameness is most prevalent has a key value regarding risk factor analysis. Each of the 491 sows from the five commercial herds in **chapter 4**, was visually assessed the day sows were moved from one stage on the farm to another (*i.e.* farrowing crates, insemination stalls, group-housing). A mean lameness prevalence of $5.9\% \pm 3.56\%$ was found although the prevalence significantly differed between herds in the range 2.3% to 11.0% ($P = 0.002$) and varied throughout the reproductive cycle ($P = 0.027$). The highest prevalence of lame sows was found after sows were housed in the individual stalls of the insemination stable ($8.7\% \pm 6.1\%$), the lowest at the end of group-housing ($4.1\% \pm 4.4\%$). These results indicate that to minimize the prevalence of sow lameness, researchers, veterinarians and farmers should focus on housing in the insemination stalls and further research should be carried out to identify influential factors that are manageable (**chapter 6**).

Finally, knowledge on the risk factors for lameness development is crucial to develop preventive strategies. This thesis focussed on the risk factors for lameness development shortly after introduction into group-housing as for this period, the highest incidence of lameness was reported by other researchers. A longitudinal study on 15 commercial herds was performed to investigate the incidence of sow lameness and possible risk factors within the first three to five days of group-housing (**chapter 5**). The median prevalence of lameness in each herd was 13.1% (0 – 27.3). Sows with more than 10% of the body covered with manure were associated with a higher odds (OR = 2.33, $P < 0.001$) for lameness development. An increase of space allowance from 1.8 m² to 3 m² (OR = 0.40, $P = 0.03$) and of herd size from 144 to 750 sows per farm (OR = 0.71, $P = 0.02$) decreased the odds for lameness development. The degree of aggression, indicated by skin lesions, nor the floor characteristics (*i.e.* wetness, slipperiness and quality) influenced lameness development. This study demonstrated that lameness development in sows within the first days of group-housing may not be increased by hierarchical aggressive encounters but that sows may benefit from a higher floor area/sow. Further research should reveal the optimal floor space allowance

Summary

necessary to prevent lameness development. The relationship between sow lameness on the one hand and sow dirtiness and herd size on the other hand should be elucidated and influential factors need to be defined to find measures to prevent sow lameness (**chapter 6**).

SAMENVATTING

Kreupelheid is het voornaamste klinische symptoom van beenwerkproblemen. Voor zeugen houdt kreupelheid uitermate belangrijke welzijns- en gezondheidsproblemen in. Voor de varkenshouder kan een hoog aantal kreupele dieren leiden tot zware financiële verliezen. De verplichte groepshuisvesting van drachtige zeugen sinds 2013 werd voornamelijk ingevoerd omwille van welzijnsoverwegingen. Het voorkomen van kreupele zeugen blijkt echter hoger te zijn in groepshuisvesting. Preventie van kreupelheid is noodzakelijk om het welzijn en de gezondheid van de dieren te garanderen, om het arbeidsplezier van de veehouder te bevorderen, om de financiële verliezen terug te dringen en om zodoende mee te werken aan een duurzamere varkenshouderij.

Uit de literatuurstudie (**hoofdstuk 1**) is gebleken dat nog op drie belangrijke vlakken verder onderzoek nodig is om te kunnen komen tot een gedegen preventie van kreupelheid bij zeugen. Ten eerste gebeurt de detectie van kreupele zeugen tot dusver aan de hand van visuele score methodes. Deze methodes zijn echter subjectief, vertonen vaak een lage overeenkomst tussen observatoren en zijn weinig gevoelig om dieren die slechts in geringe mate mank zijn op te sporen. Meer objectieve, accurate en precieze methoden gebaseerd op kinematische en kinetische technieken werden reeds succesvol gebruikt voor de detectie van kreupelheid bij andere diersoorten maar ontbreken tot dusver voor zeugen. Daarnaast is het belangrijk dat de varkenshouders gemotiveerd worden om preventieve maatregelen op te nemen in de dagelijkse bedrijfsvoering. Een goed begrip van de economische gevolgen blijkt hiertoe een sterke drijfveer te zijn. De financiële verliezen veroorzaakt door kreupelheid bij zeugen zijn deels te wijten aan de (in)directe impact op de reproductie. Als er veel zeugen kreupel zijn, kan het percentage dieren dat wordt afgevoerd naar het slachthuis sterk stijgen. Daardoor neemt het aantal nieuw aangevoerde jonge zeugen op het bedrijf toe. Jonge zeugen zijn minder productief dan oudere dieren waardoor kreupelheid indirect kan leiden tot een daling van de reproductieresultaten. Dit indirecte effect werd reeds aangetoond in onderzoek. Over de vraag of een kreupel dier zelf ook minder productief is (het directe effect), bestaat echter nog onduidelijkheid. Ten slotte is het uitwerken van preventieve maatregelen enkel mogelijk

wanneer de factoren gekend zijn die bijdragen tot de ontwikkeling van kreupelheid. Tot nog toe is onderzoek naar dergelijke risicofactoren voor kreupelheid bij zeugen in groepshuisvesting beperkt.

De doelstelling van dit doctoraat (**hoofdstuk 2**) was om de preventie van kreupelheid bij zeugen te stimuleren door de detectie van kreupelheid te bevorderen, de impact op productie en reproductie te verduidelijken en door risicofactoren voor kreupelheid op te sporen.

Om tot een beter detectie van kreupele zeugen te komen, werd een toestel ontwikkeld dat kinetische en kinematische stand variabelen meet aan de hand van weegschaal- en beeldanalyse: 'SowSIS (Sow Stance Information System)' (**hoofdstuk 3**). Het toestel is demonteer- en transporteerbaar, praktisch voor gebruik op commerciële bedrijven en detecteert kreupelheid bij zeugen in stilstand. De accuraatheid van de krachtplaten werd beoordeeld door het meten van ijkgewichten met een massa van 5kg tot 175kg. De krachtplaat analyse was uitermate accuraat ($R^2 \approx 1$), ongeacht de positie van de ijkgewichten ten opzichte van de weegcellen en ongeacht de duur van de metingen. De precisie van het toestel werd bepaald door 20 drachtige zeugen die bij visuele score geen kreupelheid vertoonden, vijf maal na elkaar te meten met het ontwikkelde toestel. Zowel de kinetische als kinematische stand variabelen vertoonden een voldoende hoge herhaalbaarheid (variatiecoëfficiënt $\leq 15\%$). Enkel voor het aantal en de duur van zowel het opheffen van een poot als van gewichtsverschuivingen tussen poten, werd een hoge variatie gevonden tussen de herhaalde metingen binnen eenzelfde dier. Om de invloed van kreupelheid op de gewichtsverdeling te beoordelen, werd een preliminair onderzoek uitgevoerd. Vier gezonde zeugen en vier zeugen die mank waren op de rechter achterpoot werden gemeten met het ontwikkelde toestel. Manke en gezonde zeugen hadden een vergelijkbare leeftijd en bevonden zich in hetzelfde stadium van de dracht. Manke zeugen belastten het manke lidmaat duidelijk minder en verschoven het gewicht voornamelijk naar de contralaterale poot. Het aantal maal dat een dier een poot opheft nam significant toe voor het manke lidmaat (gemiddeld 48 i.p.v. 23; $P < 0,001$). Ook de verhouding in belasting tussen de beide achterpoten en tussen de beide poten aan de rechter zijde was duidelijk lager ($P < 0,05$) voor manke (64% resp. 54%) dan voor gezonde zeugen (93% resp. 76%). Er kan worden geconcludeerd dat het ontwikkelde toestel praktisch, accuraat en precies is in het meten van de meeste stand variabelen en dat op basis van de kinetische stand variabelen gezonde zeugen van visueel kreupele zeugen onderscheiden kunnen worden. In verder onderzoek moet de accuraatheid van de beeldanalyse onderzocht worden en een grootschaliger onderzoek is nodig om de resultaten van de preliminaire studie te bevestigen.

Om finaal zeugen te kunnen opdelen in manke en niet manke dieren, moet een algoritme worden ontwikkeld en gevalideerd, gebaseerd op de ‘force and visual stance variables’ (**hoofdstuk 6**).

Om varkenshouders te motiveren controlemaatregelen te nemen om kreupelheid bij zeugen te beperken, moet de economische impact van kreupelheid en dan vooral de invloed op de reproductie van zeugen verduidelijkt worden. Om de impact van kreupelheid en klauwletsels op de reproductie na te gaan, werden 491 zeugen afkomstig van vijf praktijkbedrijven opgevolgd gedurende één reproductiecyclus (**hoofdstuk 4**). Er werd geen significant verband gevonden tussen kreupelheid en het spenen-bronst interval of het optreden van anoestrus, herlopen of abortus. Het verband tussen aanwezigheid van kreupelheid en de worpgegevens was beperkt tot een effect op aanwezigheid van gemummificeerde biggen. Kreupele zeugen bleken een 2,4 maal (95% BI: 1,19 – 4,75; P = 0,014) hogere kans te hebben op aanwezigheid van gemummificeerde biggen in de toom dan gezonde zeugen. Aanwezigheid van klauwletsels had een duidelijk effect op de worpgegevens van zeugen. Zeugen met witte lijn letsels en huidwonden net boven de klauw hadden respectievelijk 1,9 maal (95% BI: 1,04 – 3,51; P = 0,036) en 4,1 maal (95% BI: 1,23 – 13,8; P = 0,021) hogere kans op doodgeboren biggen. Tweeëntwintig procent van de zeugen werd tijdens de studie uit de groep genomen en ongeveer de helft daarvan werd afgevoerd naar het slachthuis of geëuthanaseerd. Kreupelheid was de tweede voornaamste reden voor afvoer naar het slachthuis. Bovendien waren zeugen afgevoerd omwille van kreupelheid significant (P = 0.01) jonger dan zeugen die werden afgevoerd om andere redenen (worpnummer: $2,6 \pm 1,3$ versus $4,0 \pm 1,8$). Kreupelheid heeft dus vooral een indirecte invloed op de reproductieresultaten door een toename van het afvoerpercentage van voornamelijk jonge zeugen. Het zijn dus niet zozeer de reproductieresultaten van de individuele zeug maar wel de globale reproductieresultaten van het bedrijf die getroffen worden. De impact van kreupelheid wordt dus vooral bepaald door de effect op de langleefbaarheid van de zeugen.

Kennis van het tijdstip waarop de meeste zeugen kreupel zijn laat toe om meer gericht te zoeken naar risicofactoren. Elke zeug (in totaal 491) werd visueel gescoord voor kreupelheid op de dag dat ze verplaatst werd naar een andere afdeling in het bedrijf, namelijk van kraamstal naar inseminatie afdeling, van inseminatie afdeling naar groepshuisvesting en vervolgens terug naar de kraamstal (**hoofdstuk 4**). Gemiddeld was $5,9\% \pm 3,56\%$ van de zeugen mank. Het voorkomen van manke zeugen verschilde echter sterk tussen bedrijven, van 2,3% tot 11% (P = 0,002) en varieerde bovendien naargelang het tijdstip in de

reproductiecyclus ($P = 0,027$). Het hoogste aantal manke zeugen werd gezien aan het einde van de periode in de inseminatie afdeling, waar zeugen in individuele boxen gehuisvest werden ($8,7\% \pm 6,1\%$), het laagste aantal aan het einde van de groepshuisvesting ($4,1\% \pm 4,4\%$). Deze resultaten duiden erop dat om kreupelheid te verminderen, onderzoekers, dierenartsen en varkenshouders aandacht moeten besteden aan de inseminatieafdeling. Verder gedetailleerd onderzoek moet gericht zijn op het vinden van factoren die de ontwikkeling van kreupelheid in deze afdeling beïnvloeden en die kunnen opgenomen worden in preventiestrategieën (**hoofdstuk 6**).

Het achterhalen van de factoren die de ontwikkeling van kreupelheid kunnen beïnvloeden, is de laatste kritische stap in het ontwikkelen van preventiestrategieën. In dit doctoraat werd de nadruk gelegd op de periode kort na introductie van zeugen in groepshuisvesting omdat voor deze periode de hoogste incidentie aan manke zeugen werd gerapporteerd door andere onderzoekers. Er werd een longitudinale studie op 15 praktijkbedrijven opgezet om de incidentie van kreupelheid bij zeugen binnen de eerste drie tot vijf dagen na introductie in de groepshuisvesting te bepalen en de ermee geassocieerde factoren te onderzoeken (**hoofdstuk 5**). Over alle bedrijven heen werd een mediaan van $13,1\%$ ($0 - 27,3$) manke zeugen gevonden. Zeugen waarvan meer dan 10% van het lichaamsoppervlak bedekt was met mest hadden $2,3$ keer (95% BI: $1.42 - 3.85$; $P < 0.001$) meer kans om kreupelheid te ontwikkelen. Een toename van de beschikbare oppervlakte per dier van $1,8 \text{ m}^2$ naar $3,0 \text{ m}^2$ ($OR = 0,40$, $P = 0,03$) en een toename in bedrijfsgrootte van 144 zeugen naar 750 zeugen ($OR = 0,71$, $P = 0,02$) verminderde het risico op de ontwikkeling van kreupelheid. Noch agressie, uitgedrukt in huidletsels, noch de vloereigenschappen (nl. vochtigheid, slipvastheid en kwaliteit) waren geassocieerd met de ontwikkeling van kreupelheid. Deze studie toonde aan dat de ontwikkeling van kreupelheid bij zeugen binnen de eerste dagen na introductie in de groepshuisvesting niet verergerd wordt door agressieve hiërarchische interacties maar dat zeugen wel voordeel kunnen halen wanneer ze beschikken over een grotere oppervlakte per dier. Verder onderzoek behoort de optimale vloeroppervlakte per dier te bepalen die nodig is om kreupelheid te voorkomen. De relatie tussen kreupelheid enerzijds en zeugbevuiling en bedrijfsgrootte anderzijds moet verder worden uitgediept en invloedsfactoren moeten worden onderzocht om mogelijke preventieve maatregelen op te sporen (**hoofdstuk 6**).

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LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviation - Symbol	Definition
BI	Betrouwbaarheidsinterval
CI	Confidence interval
CV	Coefficient of variation
GRF	Ground reaction force
IOR	Inter-observer reliability
LWS	Leg weight symmetry
NSAID	Non-steroidal anti-inflammatory drug
NRS	Numerical rating scale
OR	Odds Ratio
PNN	Probabilistic neural network
R ²	Coefficient of determination
S.D.	Standard deviation
SEM	Standard error of the mean
VAS	Visual Analogue scale

PREFACE

Pig production has long been driven by the goal to produce at the lowest cost possible which resulted in intensive large-scale production systems. In the last decades, this way of pig production became subject of criticism and concerns and the need for more sustainable production systems arose. Sustainable pig production considers many more criteria than just economic ones, including ecological issues, animal welfare and health, farmer working conditions, product quality and food safety.

Housing sows in individual stalls has been one of the most controversial welfare issues. The growing concern on housing has ultimately led to a ban on gestation stalls in the European Union from 2013 onwards. The alternative however, group-housing of pregnant sows, also presented welfare-related shortcomings including an increased risk for lameness development. Lameness has been recognized to be detrimental for the well-being and health of sows as well as for the profitability of the herd. From a welfare and economic perspective, control and prevention of lameness are required.

We hope that the insights provided in this thesis may contribute to a better understanding of sow lameness, to better control the lameness-related welfare and financial challenges of sow group-housing, and ultimately to a more sustainable pig production.

General introduction

1.1 Definition of “Lameness”

Lameness can be defined as impaired movement or deviation from normal gait or posture while a normal degree of alertness is displayed (Wells, 1984; Straw et al., 1999; Beusker, 2007). The severity of lameness can vary greatly. Lameness may be manifested as a decreased symmetry of limb movement, an alteration or shortening of stride, a reduced ability or inability to bear weight and total recumbency (Straw et al., 1999; Maas, 2009).

The ability of an animal to move is brought by the functional integration of the nervous system, bones, muscles, cartilage, tendons, joints and ligaments. Pigs are characterized by a symmetrical four-beat gait with an alternating two- and three-limb support phase and even strides. They walk in a diagonal sequence in which the hind foot touches down slightly later than the contralateral fore foot. Fore limbs carry more load, have a longer stance time and a lower swing/stance time ratio than hind limbs. Yet, the stride elevation is higher in hind limbs (Thorup et al., 2007a; von Wachenfelt et al., 2008). While standing, pigs show a merely straight back and stand squarely on all four legs. Lameness may develop when the integration of the musculoskeletal system, the nervous system or both are disturbed. Disorders can be located in the limbs as well as in the trunk of the animal, and may include painful lesions as well as mechanical defects (Wells, 1984; Smith, 1988; Beusker, 2007). Animals alter their gait in an attempt to cope with the physical incapacity and to avoid the uncomfortable or painful condition (Beusker, 2007). As such, gait problems are a manifestation of discomfort or pain and lameness is recognized as the most general clinical sign of musculoskeletal disorders (Beusker, 2007; Jackson and Cockcroft, 2007). Yet, it should be noted that an abnormal gait may not only develop as a result of disorders in the locomotor system. Problems in other organs (*e.g.* severe udder distension in heifers) or environmental factors (*e.g.* slippery floors) may also impair locomotion (Metz and Bracke, 2003).

The differential diagnosis of lameness in growing and breeding pigs is extensive (Wells, 1984; Straw et al., 1999). All components of the musculoskeletal system can be involved and claw,

foot, lower leg, thigh, shoulder and pelvis can be affected. However, in several studies joint disorders (arthritis and osteochondrosis) and claw lesions were diagnosed to be the principal causes of lameness and associated culling or euthanasia in sows (Dewey et al., 1993; Kirk et al., 2005; Heinonen et al., 2006; Sanz et al., 2007; Engblom et al., 2008; Nielsen and Haugegaard, 2012).

1.2 Prevalence of lameness

Concern over sow welfare has resulted in gestation stalls being banned in the members states of the European Union from 2013 onwards. The change to group-housing improved sow well-being in that greater opportunity for social expression and movement are provided. Yet, group-housing also raises welfare issues concerning post-mixing aggression and lameness (Gjein and Larssen, 1995a; Backus et al., 1997; Anil et al., 2003; Anil et al., 2005b; Estienne et al., 2006; Chapinal et al., 2010b). The estimated prevalence of lameness in group-housed sows differs between studies and countries, and reported values range from 8% to 17%, which is quite high (Gjein and Larssen, 1995b; Bonde et al., 2004; Heinonen et al., 2006; KilBride et al., 2009a; Pluym et al., 2011; D'Eath, 2012). When changing to group-housing lameness was believed to be more prevalent in group-housed sows than in sows housed in individual stalls. An early study by Backus et al. (1997) and recent studies by Estienne et al. (2006) and Chapinal et al. (2010b) confirmed this concern. It can be presumed that the higher incidence of lameness in group-housed sows was simply owing to better detection. Lameness is defined as a gait defect but when sows are confined in stalls, farmers are less able to assess the gait of sows as they cannot see sows walking. Yet, recent studies revealed that the association between group-housing and lameness is in fact more complex and is influenced by the type of flooring and the use of bedding. Compared to stalls on bare, slatted floors, the incidence of lameness is lower in straw-bedded group-housing systems (Karlen et al., 2007) but higher in group-housing systems using slatted floors with no bedding (Estienne et al., 2006; Harris et al., 2006; Chapinal et al., 2010b). Because bare slatted concrete floors do not require manual removal of soiled bedding and are less costly and labour- intensive, they are most often used for group-housing of gestating sows. Consequently, with the change to group-housing, an increase in the risk of lameness development may be expected. The relative high prevalence of lameness and possible increase is of major concern to both animals and farmers as

lameness can severely compromise animal welfare and health and may contribute to huge economic loss.

1.3 Importance of lameness

1.3.1 WELFARE AND HEALTH PARAMETERS

The importance of lameness with regard to animal welfare is irrefutable. Animal welfare experts consider lameness to be a main animal-based welfare indicator (Whay et al., 2003) and the condition is included in many on-farm welfare assessment schemes (Dawkins et al., 2004; Global Animal Partnership, 2009; Welfare Quality®, 2009; Anzuino et al., 2010; RSPCA, 2012).

Animal welfare has a multidimensional nature, implying that numerous criteria must be fulfilled to achieve well-being (Rushen, 2003). Several approaches have been used to list these criteria for overall welfare assessment. The one that is most commonly used is the concept of ‘the Five Freedoms’ (Table 1).

Table 1: The Five Freedoms and provisions (Webster, 2001).

Freedom ...	Provision by ...
from thirst, hunger and malnutrition	ready access to fresh water and a diet to maintain full health and vigour
from discomfort	providing a suitable environment including shelter and a comfortable resting area
from pain, injury and disease	prevention or rapid diagnosis and treatment
to express normal behaviour	providing sufficient space, proper facilities and company of the animal’s own kind
from fear and distress	ensuring conditions which avoid mental suffering

Although practical in use, this concept presents some shortcomings. As an alternative, Bracke et al. (1999) described the concept of ‘needs’ in which welfare is assessed by evaluating the different states of need satisfaction and frustration. The needs formulated for pigs included ingestion of food and water, rest, social contact, reproduction (mating, nest building and

maternal care), normal locomotion, exploration, body care (scratching and wallowing), evacuation (separation of resting and dunging area), territorialism, thermal comfort, respiration, health (reduce illness, injuries and pain) and safety (reduce danger, aggression and fear). In 2007, the European project Welfare Quality[®] developed a set of independent criteria (Table 2). The set was implemented in the Welfare Quality[®] Protocol, an animal-based methodology for overall animal welfare assessment frequently used within the European Union (Welfare Quality[®], 2009).

Lameness usually harms several welfare criteria simultaneously. Depending on the severity, lameness can affect all of the five freedoms (Anil et al., 2009a) and may have consequences for various welfare needs as defined by Bracke et al. (1999) and for many of the WelfareQuality[®] criteria.

Lame sows are less active, lay down more often, have shorter standing times and explore less compared to healthy sows (Madec et al., 1986; Valros et al., 2009). The higher level of acute phase proteins in sows that are lame due to skin infections or arthritis, indicates the presence of inflammatory processes (Heinonen et al., 2006). Cytokines released by the inflammatory processes predispose to anorexia and lethargic behaviour (Johnson, 1997). As a result, lame sows may be less motivated to walk to the feeding area. Due to the reduced locomotion ability, sows may neither be fit enough to compete for food and water. This could have been the reason why the eating rank of sows was affected by lameness in a study by Cornou et al. (2008). Besides feed intake, lameness can also reduce the sow's daily water intake (Madec et al., 1986). As a result, lame sows may suffer from hunger and thirst even when feed and water supply is sufficient. The finding that severely lame sows were often in poor body condition may support this (Bonde et al., 2004; Tarres et al., 2006).

Table 2: Set of (sub)criteria used in WelfareQuality[®] for sows to develop an overall welfare assessment (Welfare Quality[®], 2009) .

Criteria	Sub-criteria	Specifications
Good feeding	1. Absence of prolonged hunger	
	2. Absence of prolonged thirst	
Good housing	3. Comfort around resting	Assessed through behaviour (including rising up and lying down movements) but not injuries (included in 5).
	4. Thermal comfort	
	5. Ease of movement	Not considering health problems (included in 6, 7, 8) and movements around resting (included in 3).
Good health	6. Absence of injuries	Except those produced by a disease or voluntary interventions (<i>e.g.</i> mutilations).
	7. Absence of disease	Absence of clinical problems other than injuries.
	8. Absence of pain induced by management procedures	<i>e.g.</i> mutilations and stunning
Appropriate behaviour	9. Expression of social Behaviour	Balance between negative (<i>e.g.</i> aggression) and positive (<i>e.g.</i> social licking) aspects.
	10. Expression of other behaviour	Balance between negative (<i>e.g.</i> stereotypies) and positive (<i>e.g.</i> exploration) aspects.
	11. Good human-animal relationship	No fear of humans
	12. Positive emotional state	Except fear of humans

Lameness is often a painful condition. Administration of non-steroidal anti-inflammatory drugs (NSAID) have been found to alleviate the degree of lameness in sows (Mustonen et al., 2011), cattle (Flower et al., 2008), horses (Keegan et al., 2008), broiler chickens (Danbury et al., 2000), cats (Lascelles et al., 2001) and dogs (Doig et al., 2000). Although it is associated with discomfort, pain in the short term may also aid in the healing process by allowing animals to rest. However in the long run, pain reduces feed intake, body condition and milk production, increases piglet mortality due to savaging and may even lead to hyperalgesia (Bonde et al., 2004; Anil et al., 2005a; Chen et al., 2008). Chronic lameness associated with chronic pain is immunosuppressive increasing the susceptibility of an animal to disease. The reduced daily water intake in lame sows (Madec et al., 1986) and decreased activity and standing time (Madec et al., 1986; Valros et al., 2009) clearly predispose lame sows to develop urinary tract infections. As lame sows lay down more often, faecal contamination of the perineal region may occur, facilitating vaginal contamination and ascending infections in the urinary and reproductive tract resulting in reduced fertility (Dee, 1992). Moreover, pyelonephritis and endometritis are both an important cause of sow mortality (Chagnon et al., 1991).

Lame sows tend to be sniffed more by healthy sows and may suffer from increased social pressure (Heinonen et al., 2013). Good locomotion supports normal behaviour and enables an animal to cope with its environment. Lame sows, with reduced mobility, might experience reduced ability to adapt to adverse situations such as agonistic behaviour, competition or poor floor quality (Anil et al., 2009a). As a consequence the freedom from fear and distress might be violated.

Lameness does not only affect animal welfare but can also be detrimental to the farmer's welfare. High percentages of diseased sows, amplified work-load and financial losses may reduce motivation of on-farm work.

1.3.2 PRODUCTION AND FINANCIAL PARAMETERS

Besides the welfare problems, also the economic losses associated with lameness are an important concern for pig producers. The financial loss due to lameness has been estimated to be 37 € per lame sow in Germany (Grandjot, 2007), 180 \$ per lame sow in the USA (Deen et al., 2008) and 20 to 30 € per sow present in the farm in a Dutch study (Schuttert, 2008).

Financial loss can be attributed to increased work-load, higher veterinary costs for treatment or euthanasia, higher risk for total or partial carcass condemnation resulting in less slaughter revenue and less pig's feet for culinary purposes (Gils et al., 2013), secondary diseases, increased sow mortality and the impact on productivity (Rowles, 2001; Schuttert, 2008). The association between lameness and reproductive performance can be either indirect or direct. Indirectly, lameness may affect (re)production and profitability through its impact on sow longevity, feed intake, health and behaviour. Lameness is a main reason for euthanasia, mortality and involuntary culling of sows resulting in lower average longevity of sows (Abiven et al., 1998; Lucia et al., 2000b; Kirk et al., 2005; Engblom et al., 2007; Engblom et al., 2008; Anil et al., 2009b; Jensen et al., 2010). The average parity of sows, when removed from the herd due to lameness, range between 2.6 and 3 litters (D'Allaire et al., 1987; Lucia et al., 2000b; Engblom et al., 2007). To obtain a positive cash flow, at least three litters are required from a sow (Lucia et al., 2000a; Stalder et al., 2003). Hence, lame sows are removed from the herd before optimal productivity is attained and investment costs are repaid. Premature culling of sows increases the replacement rate and results in an imbalanced parity distribution with a shift towards more young sows. As young sows are less productive, the mean litter size and the number of pigs weaned per sow per year decrease (D'Allaire et al., 1987; Dewey et al., 1995; Tantasuparuk et al., 2000; Engblom et al., 2007).

As mentioned before, lameness may be associated with reduced feed intake. Inadequate feed intake during lactation can undermine subsequent reproductive performance including an increased weaning-to-oestrus interval as well as a higher risk to develop anoestrus or to return to service (Koketsu et al., 1996). Lameness may also affect the ability of a sow to make postural changes within the farrowing crate. According to (Bonde et al., 2004), lameness leads to uncontrolled lying-down behaviour (*i.e.* lying down from a standing position) which has been reported to be an important cause of crushing piglets (Weary et al., 1998). Lame sows are more susceptible to diseases, especially urinary and reproductive tract infections which have been associated with reduced fertility. The higher risk for early culling, reduced feed intake, crushed piglets and secondary infections indirectly decline productivity of either the sow and the herd.

Compared to the indirect effect of lameness on sow productivity, the direct effect is far less described in literature and results are much more inconsistent. Several studies did not find any effect (Kroneman et al., 1993a; Andersen and Bøe, 1999; Heinonen et al., 2006; Willgert, 2011) while other studies described a negative relationship between lameness and farrowing

performance (Grandjot, 2007; Anil et al., 2009b). Comparison between these studies is difficult as different scoring methods and different stages in the reproductive cycle were used to assess lameness. As sows can recover from lameness over time, it may be recommended to assess lameness in the same sows at different times throughout the reproductive cycle. In addition, knowledge on the stage in the reproductive cycle at which lameness is most prevalent, may have a key value regarding risk factor analysis and may lead to a more focused control program.

1.4 Detection of lameness

1.4.1 SUBJECTIVE METHODS

Visual assessment is most commonly used to detect lameness in (farm) animals. Several scoring systems have been used for a wide range of animal species including sows and finishing pigs (Table 3). The common principle is that animals are assigned a score while standing and walking based on aspects of their gait, posture and behaviour.

Visual lameness scoring can be performed by means of on-farm live scoring (Main et al., 2000; Grégoire et al., 2013) or analysis of video recordings (D'Eath, 2012). Scores are assigned on a numerical rating scale (NRS) or a visual analogue scale (VAS). A NRS uses discrete ordered categories (D'Eath, 2012) whereas a VAS scores lameness on a continuous scale (Nalon et al., 2012). In practice, a VAS is usually a 100 mm long horizontal line anchored by the minimum and maximum score at each end. Observers make a mark on the line at the point that represents their perception of the magnitude or extent of the assessed gait, posture or behavioural variable. Continuous scales have been reported to be more sensitive than ordinal scales in that they allow observers to record more subtle changes (Welsh et al., 1993; Engel et al., 2003; Quinn et al., 2007). However, the better resolution of a continuous scale is at the cost of greater variation in the data (Engel et al., 2003; Quinn et al., 2007). A modified scale in which the thresholds of a numerical rating scale are indicated on a continuous scale may reduce the risk of drift and variation within and between observers while the advantages of a continuous scale are maintained. The potential of such a modified VAS was recently reported for the assessment of lameness in cattle (Tuytens et al., 2009) and sows (Nalon et al., 2013).

Table 3: Visual lameness scoring systems for gilts, sows and finishing pigs used by different authors

Author	Score	Description
Dewey et al. (1993)	0	Normal gait
	1	Stiff gait: mild
	2	Stiff gait: moderate
	3	Stiff gait: severe
	4	Lame: mild
	5	Lame: moderate
	6	Lame: severe
	7	Requires assistance to stand and then can walk
	8	Can stand with assistance but then falls
	9	Cannot stand with assistance
Main et al. (2000) ^a	0	Bright, alert, responsive, inquisitive, active in group, stands squarely on all four legs, even strides, accelerate and rapidly change direction
	1	See score 0 but uneven stride length and stiffness
	2	Apprehensive to boisterous pigs, uneven posture, shortened stride, lameness detected, swagger of caudal body, still agile
	3	Bright but less responsive, last to leave pen, remains separate from group activity, uneven posture (no weight bearing on affected leg), shortened stride, caudal swagger, still gallops and trots
	4	May be dull, unwilling to leave familiar environment, separate from other pigs, affected limb elevated off floor while standing and not placed on floor while moving, visibly distressed
	5	Dull, unresponsive, distressed by other pigs but unable to respond, does not stand unaided, does not move
Bonde et al. (2004)	1	No signs of lameness
	2	Stepping frequently while standing
	3	Attempts to relieve limb
	4	Reluctance to bear weight on limb
Karlen et al. (2007)	0	Unaffected ability to stand and move, symmetrical limb movements
	1	Not lame, unaffected ability to stand and move, equal weight bearing but compromised movement
	2	Moderately lame, reduced ability to stand, diminished and difficult movement, refuse to put weight on affected leg, frequently lifting affected feet from the ground
	3	Severely lame, restricted ability to stand and move, unable to put weight on affected leg, often swollen joints, stiffness and squealing when moved

^aIdentical or adapted version used by Estienne et al. (2006), Harris et al. (2006), Killbride et al. (2009), Mullan et al. (2011), D'Eath (2012) and Grégoire et al. (2013)

Table 3: Continued

Author	Score	Description
Geverink et al. (2009)	0	Normal gait
	1	Swagger of caudal body, shortened stride
	2	Reduced weight bearing on affected limb
	3	No weight bearing on affected limb, does not move
Welfare Quality [®] (2009)	0	Normal gait, difficulties walking, still using all legs, stride may be shortened and swagger of caudal body
	1	Severely lame, resists weight bearing on affected limb
	2	No weight-bearing on affected limb, unable to walk
Feet First [®] (2009)	0	Moves easily with little inducement, comfortable on all feet
	1	Lameness apparent: reluctant to bear weight on affected leg but still easily moves within pen
	2	Lameness in one or more limbs, compensatory behaviour such as dipping the head and arching the back
	3	Real reluctance to walk and bear weight on one or more limbs, difficult to be moved
Mustonen et al. (2011)	0	No lameness
	1	Minimal lame: stiff, ataxic or swaying gait, shortened stride
	2	Slightly lame: limp visible, animal unconcerned and exercises normally
	3	Moderately lame: obvious limp with head bobbing, difficulty with exercise, moderate kyphotic posture
	4	Severely lame: barely or no weight bearing, able to move, severely kyphotic posture
Nalon et al. (2012)	continuous	Visual analogue scale
Karriker et al. (2013)	0	Moves freely, uses all four limbs and feet evenly
	1	Weight-shifting away from affected limb upon standing, no limping when walking
	2	Obviously shifts weight away from affected limb when standing, limping or adaptive behaviour (head bob, quickened step on affected limb) when walking
	3	Reluctant to stand or walk, obvious limp and adaptive behaviour when walking
	4	No weight bearing on affected limb when either standing or walking

Visual observation does not need instrumentation and is easy to use, cheap and feasible to perform on-farm what explains the widespread use of visual scoring systems. Nevertheless, visual assessment of the gait and posture of sows, and pigs in general, can be challenging. Although very different in appearance, domesticated pigs still share most of their relatives' instincts peculiar to prey species. Lamé pigs may show guarding behaviour meaning that the animals may be experiencing painful or mechanical difficulties but exhibit normal behaviour to avoid detection by predators (*e.g.* men), until injuries are advanced (Weary et al., 2009; Anil et al., 2009a). Especially when separated from the group and in the presence of a human observer, hiding behaviour may be distinct (Nielsen, 2011). This stoical nature however hampers detection of lameness. In addition, pigs have a stilted locomotion and they rather develop a short rapid locomotion than a steady walking or trotting when they are urged to move (Main et al., 2000). Asymmetry in vertical head and sacral bone movements have been used to detect and quantify the degree of lameness in horses (Keegan et al., 2001; Keegan et al., 2004). The relatively short neck of pigs limits the potential of detecting vertical head movements (Main et al., 2000). In addition to the animal-based limitations, visual scoring systems are subjective and hence prone to observer error (Petersen et al., 2004). However, consistent scoring, both within and between observers, is of major importance for several reasons. First, observer agreement is necessary to identify lame animals that are in pain and discomfort and that need treatment (Nielsen et al., 2010; Mullan et al., 2011). Secondly, making a correct estimation of the on-farm lameness prevalence is important (Mullan et al., 2011) and is also required to evaluate the effectiveness of remedial measures and preventive strategies. A correct diagnosis of lameness is also a key feature in risk factor analysis and is essential when selecting future breeding stock (Nielsen et al., 2010). Finally, consistent scoring is critical to the success of farm assurance audits as an assessor's decision determines whether farmers will be penalized or rewarded (Mullan et al., 2011; D'Eath, 2012). Visual locomotion scoring systems used in sows and finishing pigs typically show moderate inter-observer reliability (IOR) (Main et al., 2000; Petersen et al., 2004; D'Eath, 2012). Geverink et al. (2009) reported high IOR based on the high Pearson correlation between observers. However, Pearson correlation coefficients do not detect systematic errors and hence a high correlation between observers does not necessarily mean that they agree (Bruton et al., 2000). Although the inter-observer reliability is generally moderate, observers often experience difficulties to distinguish between healthy and slightly lame animals (Kaler et al., 2009; D'Eath, 2012). An increase in observer variability when assessing moderately instead of severely lame sheep was found by Welsh et al. (1993) and Kaler et al. (2009). Quinn et al.

(2007) reported low agreement unless lameness in dogs was severe. In sows, inter-observer reliability was worse (D'Eath, 2012) and sensitivity and specificity were lower (Anil et al., 2008a) when scoring minor locomotion anomalies. These results indicate that visual scoring may be reliable to detect clearly lame animals but may fail to detect subtle changes in posture and gait. However, rather than identifying sows at severe stages of lameness, when costs of treatment are high and recovery is slow, methods are required to identify them at the early stages of lameness.

1.4.2 OBJECTIVE METHODS

The change to group-housing of sows may have facilitated lameness detection as farmers now can observe sows during walking. However, group-housing may also give rise to difficulties for monitoring individual sows in a group. Concomitantly, as farms grow larger, the ratio of sows to farm personnel may increase, reducing again the likelihood that a lame sow will be detected and treated in a timely fashion.

Consequently, there is a need to develop more objective, sensitive and reliable methods for studying locomotion problems in pigs. Quantitative technological systems are observer independent and have the advantage that they can be automated. Automatic systems may enable long-term follow-up of an animal and might support the farmer in his daily management. Various biomechanical techniques have been developed to evaluate gait and posture and to quantify the degree of lameness in animals. Both kinematic and kinetic methods have been used. Kinematics analyse movement and posture in terms of spatial (*e.g.* stride length) and temporal (*e.g.* stance time) measurements without considering the causative forces. In fact, kinematics quantify the features of gait and posture that are assessed qualitatively by visual scoring systems. Kinetics however, consider the internal and external forces that ultimately produce movement (Clayton and Schamhardt, 2013).

KINEMATIC-BASED TECHNIQUES

Video-based motion analysis with image processing software has already been used for lameness detection in horses (Peloso et al., 1993; Keegan et al., 2004), cattle (Flower et al., 2005; Song et al., 2008) and chickens (Reiter and Bessei, 1997). Animals pass thereby one by one, freely or at hand, along one or more (high speed) cameras. Coordinates of anatomic

points of the animal can be manually determined after filming. However, most often the body of the animal is schematized with markers on anatomic reference points before video recording starts. Both passive and active markers exist. Passive markers (*e.g.* acrylic paint and retro-reflective material) only detect or reflect a signal whereas active markers really transmit a signal (Clayton and Schamhardt, 2013). For two dimensional analysis, circular, flat markers are used and the camera is oriented perpendicular to the plane of interest. For three dimensional studies, camera positioning is less important as long as each spherical marker is visible to at least two cameras at all time (Clayton and Schamhardt, 2013). Marker location depends on the purpose of the analysis. The head, dorsal midline of the pelvis and centers of joint rotation on both fore- and hind limbs are primarily used for lameness detection (Keegan et al., 2004; Flower et al., 2005; Clayton and Schamhardt, 2013). In pigs, high speed cinematography has been used already to characterize the gait in healthy animals and to determine the impact of different floor conditions and diets (Calabotta et al., 1982; Applegate et al., 1988; Thorup et al., 2007a; Thorup et al., 2007b; von Wachenfelt et al., 2008; Thorup et al., 2008; von Wachenfelt et al., 2009a; von Wachenfelt et al., 2009b). Yet for lameness detection, marker-based cinematography was only recently evaluated in sows (Fig. 1) (Grégoire et al., 2013; Stavrakakis et al., 2013). Although successful in quantifying gait and lameness, the complicated set-up and expensive equipment restrict video-based gait analysis to research setting.

Footprint or trackway analysis is a less common kinematic alternative to video-based motion analysis in farm animals. By making the animals walk on a pressure-sensitive mat (Carvalho et al., 2009) or on a floor covered with clay (Grégoire et al., 2013) or a mixture of slurry and lime powder (Telezhenko and Bergsten, 2005), footprints may be recorded. Variables such as the stride length, overlap, step angle, step asymmetry and contralateral, ipsilateral and diagonal footprint distances can be calculated. Trackway analysis on clay could not discriminate sound sows from lame sows in a study by Grégoire et al. (2013). Yet the slightly wet clay may have appeared slippery to the sows and may have influenced the sows' gait pattern (Thorup et al., 2007a; von Wachenfelt et al., 2008). Improvement of the technique and reassessment of its use as a lameness detection tool is needed.

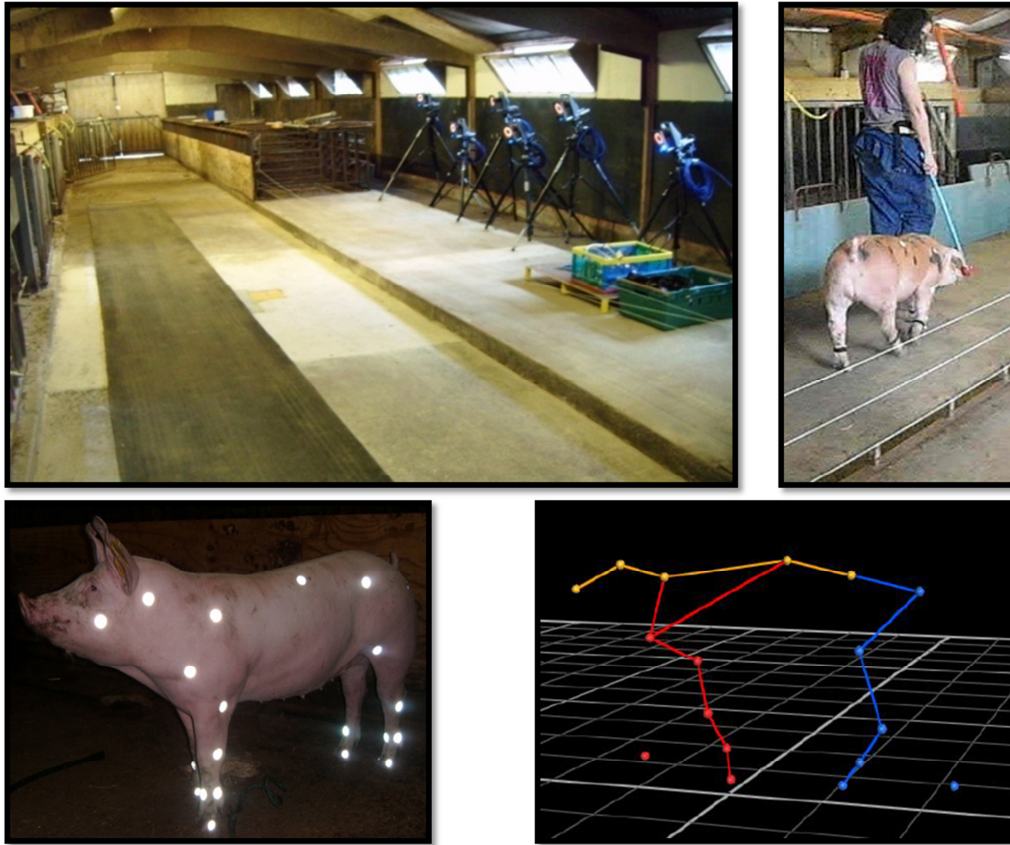


Fig. 1. A 3D Motion Capture camera system for biomechanical gait assessment in pigs. Reflective markers are placed on the body surface of the pigs at anatomical landmark positions. The infrared cameras track the markers and generate three coordinates for each marker (Source: S. Stavrakakis, Newcastle University).

Lameness may affect feeding (Cornou et al., 2008), social (Heinonen et al., 2013) and postural behaviour (Bonde et al., 2004) as well as general activity (Madec et al., 1986; Valros et al., 2009) of sows. The subjective numerical scoring system developed by Main et al. (2000) takes this into account. By use of accelerometers (Fig. 2) feeding, rooting, walking and lying behaviour can objectively be monitored (Cornou and Lundbye-Christensen, 2008). Accelerometers are sensors, fixed to an animal, that tracks acceleration measurements in three dimensions and allow activity data to be recorded at any time (Cornou and Lundbye-Christensen, 2008). They can be fitted to the limbs, the dorsum, the head and a neck collar or an eartag. Successful detection of lameness using accelerometers has been reported for horses (Keegan et al., 2004; Keegan et al., 2012), cattle (Pastell et al., 2009; de Mol et al., 2013) and recently also for sows (Grégoire et al., 2013). Further research should reveal whether

accelerometers are also capable to detect incipient lameness at an earlier stage than visual assessment.

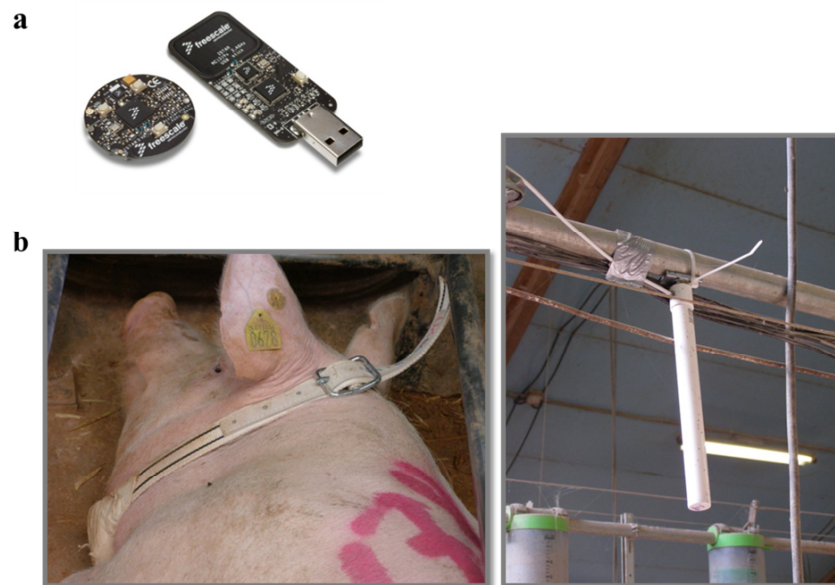


Fig. 2. **(a)** An accelerometer device with ZigBee protocol: 3-axes accelerometer transmitter board (left) and USB transceiver node (right). The device can be fitted to the ear tag of the sow. **(b)** An 'older' prototype of an accelerometer, fixed on a neck collar and the blue tooth antenna for transmission (Source: C. Cornou, University of Copenhagen).

KINETIC-BASED TECHNIQUES

Besides the kinematic analyses, also kinetics have been used for gait and posture research including force plates and pressure-sensitive walkways. Considering lameness detection, force plates have been used for both dynamic and static examinations whereas pressure sensitive walkways have merely been used for dynamic examinations.

Dynamic examination

Following Newton's third law, forces exerted against the ground by a hoof, claw or paw during walking are counteracted by an opposing force of equal magnitude, the ground reaction force (GRF). The resolved forces of GRF (Fig. 3) in vertical, longitudinal and transverse components are not visible but can be measured by a force plate (Clayton, 2005). Force plates can differ in complexity and may be divided in basic types that can measure only

the vertical component of GRF and the more sophisticated types (multicomponent force plates) that can measure all three components of GRF.

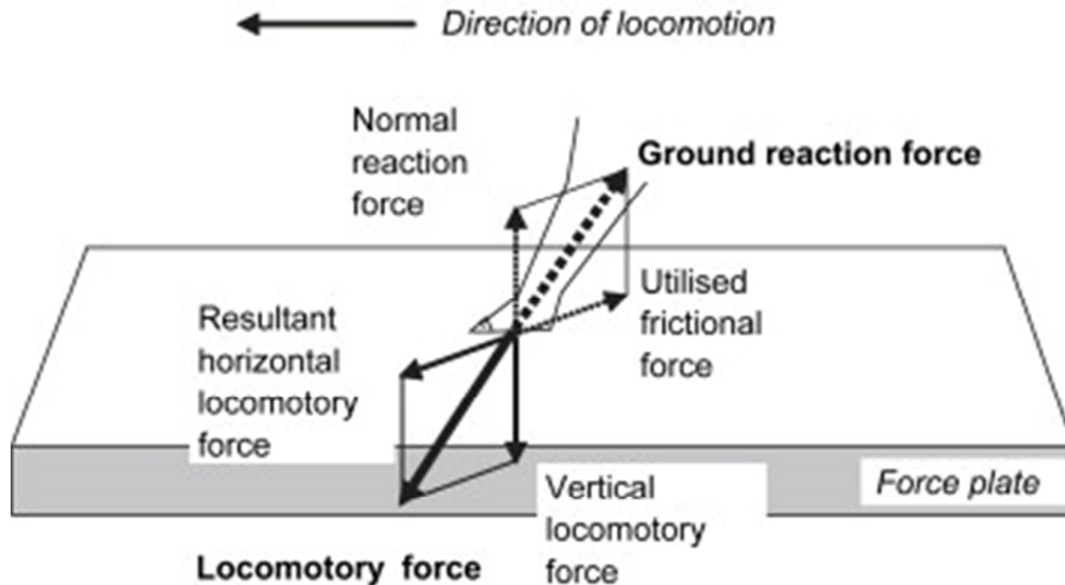


Fig. 3. The locomotory force and corresponding ground reaction force components at the claw in the initial part of stance phase of a walking pig (Source: von Wachenfelt et al., 2009b).

A force plate used for dynamic gait analyses principally consists of an in-ground metal plate with force transducers that measure the forces when animals walk across the plate. Such devices have been used extensively for clinical gait assessment in humans (Veltink et al., 2005) as well as horses (Ishihara et al., 2005; Oosterlinck, 2011; Keegan et al., 2012), cattle (Rajkondawar, 2002; Van der Tol et al., 2003; Van der Tol et al., 2005), swine (Thorup et al., 2007a; Thorup et al., 2008; von Wachenfelt et al., 2009a; von Wachenfelt et al., 2009b), chickens (Corr et al., 2007), dogs (Quinn et al., 2007), rodents (Zumwalt et al., 2006) and even bat species (Riskin et al., 2009) and wood ants (Reinhardt et al., 2009). With regard to lameness detection, dynamic force plate measurements are considered to be the reference standard in horses. They even have been suggested to be able to identify subclinical lameness in the horse (Ishihara et al., 2005). Yet, force plates are unable to simultaneously record successive strides of more than one limb. In an attempt to overcome these disadvantages, modifications like a force-measuring horseshoe (Kai et al., 2000) and a treadmill-mounted force plate (Weishaupt et al., 2002) were manufactured. In view of lameness detection in

dairy cattle, Rajkondawar et al. (2002) developed a walkthrough device consisting of two parallel basic force-plates and a corresponding mathematical lameness scoring system. Tasch and Rajkondawar (2004) developed the SoftSeparatorTM algorithm to separate the records of a group of animals that walk through the system into individual files. Based on their work, Boumatic launched the StepMetrix[®] that has proven its potential to discriminate visually lame from sound cows. A force mat made of electromechanical film, Emfit, has also been demonstrated to give promising results for bovine lameness quantification (Pastell et al., 2008b).

Pressure mats or walkways may provide a practical alternative to dynamic force plate measurements. Compared to force plates, pressure plates present additional information, as spatial variables (*e.g.* stride length) as well as the contact area and pressure distribution under each hoof, claw or paw can also be obtained. Pressure distribution plates can be used as a stand-alone device or can be assembled on a force plate. However, a built-in fixed pressure plate is only feasible in a research setting whereas portable pressure plates offer the advantage for routine clinical use. In view of lameness detection, pressure sensitive platforms and walkways offer a reasonably priced, quick and objective method for horses (Oosterlinck et al., 2010), cattle (Maertens et al., 2011), dogs (Oosterlinck et al., 2011) and cats (Romans et al., 2004). A pressure measurement system (MatScan[®], Tekscan Inc., South Boston, MA) has already been used in pigs to study claw pressure distribution, to determine its association with known claw pathologies and to test the cushioning effect of rubber mats (Carvalho et al., 2009). Recently, a pressure mat (GaitFour[®], CIR systems Inc., Havertown, PA) was used to assess experimentally induced unilateral lameness in sows (Fig. 4). As sows walked over the mat, a decreased peak pressure and stance time for the lame foot as well as a shift of weight towards the non-lame foot was revealed (Karriker et al., 2013).

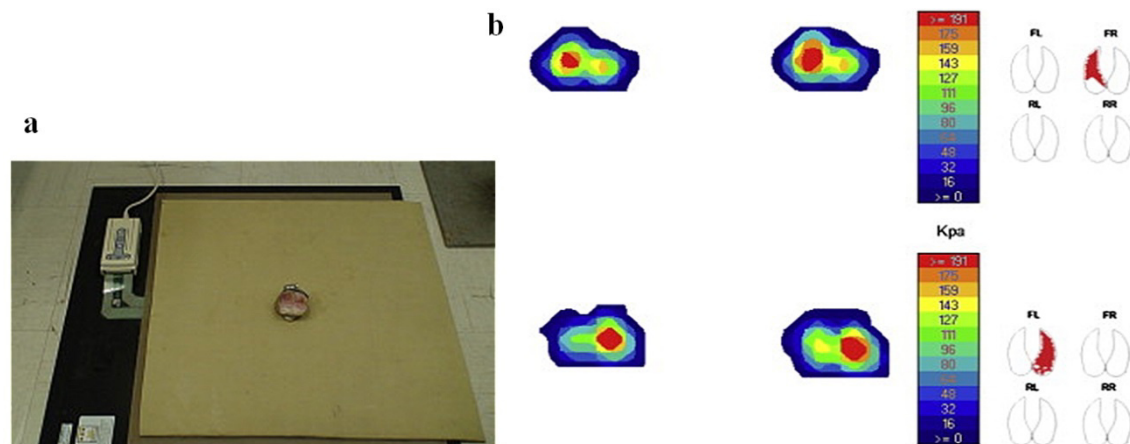


Fig. 4. (a) View on the MatScan ® Pressure Measurement System. (b) Software image of the pressure distribution on the front right and left claws (left upper and lower figures), with the respective applied loads, and the two diagrams of highest stress (right upper and lower figures), respectively (Source: Carvalho et al., 2009).

Static examination

Force plates and pressure sensitive walkways have frequently been used for lameness detection in animals at walk. However, measuring the load distribution among limbs when animals are standing may be easier to implement on farm. This would certainly be an advantage for pigs as the locomotion of these animals is difficult to control. Devices to quantify the load exerted by each leg separately, principally consist of four separate balances, one for each leg. Based on such devices it has been reported that lame animals place less weight on the injured leg and transfer weight primarily to the contralateral leg when standing (Pastell et al., 2006; Neveux et al., 2006; Rushen et al., 2007; Kujala et al., 2008; Pastell et al., 2008a). Moreover, there is a greater shifting of weight over time between the contralateral legs (Hood et al., 2001; Neveux et al., 2006; Rushen et al., 2007) and this increased variability would be a better representation of lameness than the actual amount of weight exerted on each leg (Rushen et al., 2007; Chapinal et al., 2010a). In horses, quantification of the load applied to each limb has been reported to be of value for detecting acute laminitis, grading severity of lameness and monitoring rehabilitation of chronic laminitis (Hood et al., 2001). In dairy cattle, a four-balance system also proved to be a good method for lameness detection, recognizing lameness more quickly and accurately than visual scoring (Neveux et al., 2006;

Pastell and Kujala, 2007; Rushen et al., 2007; Kujala et al., 2008; Pastell et al., 2010; Chapinal et al., 2010a). However, detection of lameness due to joint problems can be difficult (Kujala et al., 2008). Besides the amount of and variability in weight applied on each leg, the frequency of stepping (*i.e.* weight shuffling) and kicking (*i.e.* lifting a leg up) has also been reported to be a good indicator of bovine lameness (Pastell and Kujala, 2007; Pastell et al., 2008a). Measurement of how animals distribute their weight when standing may also hold promise as a method of automated detection of lameness in sows (Sun et al., 2011). However, this study only focused on deviations in the left-to-right and front-to-hind distributions. Stepping behaviour in sows, corresponding to kicking behaviour in cattle as defined by Kujala et al. (2008), has recently been investigated by use of an accelerometer (Grégoire et al., 2013). A higher number of steps was found for lame sows and stepping behaviour while standing was concluded to be a promising sow lameness indicator to be observed at farm.

1.5 Risk factors

1.5.1 INTRODUCTION

Knowledge about the risk factors for lameness is of great importance as it constitutes the basis for proper control and preventive measures. Yet risk factor analysis for lameness in group-housed sows may be complex. According to feeding method (7 main types), group stability (static or dynamic) and use of bedding, there are at least 28 options to manage group-housed gestating sows. Moreover, many infectious agents, various factors related to management and different features of the sow may be involved in the development of lameness. Management factors include housing (Salak-Johnson et al., 2007; KilBride et al., 2009a), nutrition (Done et al., 2012; van Riet et al., 2013) and rearing management (Jørgensen and Sørensen, 1998; Rowles, 2001; Gill, 2007). Sow factors include breed (Heinonen et al., 2006; Oravainen, 2008), parity (Gjein and Larssen, 1995b; Geverink et al., 2009) and conformation (Tiranti and Morrison, 2006; Díaz et al., 2013). As the study on risk factors performed as part of this dissertation mainly concentrated on housing, the relationship between housing and lameness will be discussed in detail in this introduction.

1.5.2 HOUSING

A gestation facility that houses sows in group needs to be well designed to ensure the lifetime performance, longevity and well-being of the sows are optimized and preserved. Although the change to group-housing was primarily driven by welfare concerns, it has been demonstrated that group-housing still may harm some aspects of the sow's well-being including injuries caused by aggressive encounters and an increased prevalence of lameness (Gjein and Larssen, 1995a; Backus et al., 1997; Anil et al., 2003; Anil et al., 2005b; Estienne et al., 2006; Chapinal et al., 2010b). Housing may affect the risk of lameness development in two ways: directly through its impact on the components of the locomotor system and indirectly by influencing the number and type of movements sows can make. Floor space per sow, group size, pen design and flooring are the main components of group-housing that may be involved in lameness development.

FLOOR SPACE, GROUP SIZE AND PEN DESIGN

Floor space, group size and pen design for sow group-housing have already been studied in relation to the sows' reproductive performance, body condition, skin lesions, aggression and social behaviour (Barnett et al., 1993; Weng et al., 1998; Leeb et al., 2001; Séguin et al., 2006; Salak-Johnson et al., 2007; Remience et al., 2008; Hemsworth et al., 2013; Rioja-Lang et al., 2013). Yet, studies investigating the impact on lameness development are scarce or even lacking. In a study by Salak-Johnson et al. (2007), three static social groups of five sows per group were assigned to 1.4, 2.3 and 3.3 m² of floor space per sow, respectively. Sows were fed using floor feeding. No space effect on lameness could be found within the first 13 days of group-housing but in the weeks thereafter, a high space allowance was related to an increased risk of lameness. Similarly, an increased risk of abnormal gait in the most loosely-stocked pigs has been reported for finishing pigs (KilBride et al., 2009a). Animals allocated to a high floor space may have had greater opportunity for activity which may have increased the risk of injuries leading to lameness. In addition, the effect of space allowance on lameness development may be dependent on group size. In finishing pigs, restricted floor space resulted in greater lameness scores in large groups (n = 108) but reduced scores in small groups (n = 18) (Street and Gonyou, 2008). The group size used by Salak-Johnson et al. (2007) was rather small and this could have been a reason why the higher space allowance increased the risk of

sow lameness in this study. Furthermore, studies on aggressive and social behaviour of sows revealed that space requirements not only differ according to group size but also to group stability, pen design and feeding system (Weng et al., 1998). This may also apply to lameness development. Therefore, care must be taken when attempting to generalize the results found by Salak-Johnson et al. (2007) to situations of different group size, group stability, pen design or feeding method. Differences in herd-related factors (*e.g.* group size, feeding system, group stability, floor type) could have been the reason why Gjein and Larssen (1995b) and Heinonen et al. (2006) did not find a significant association between space allowance and lameness in group-housed sows. However, the lack of a detailed herd description for each of the floor space categories used in the study by Gjein and Larssen (1995b) and Heinonen et al. (2006), made it impossible to determine whether the absence of a significant effect could be due to confounding or interaction among different herd-related factors.

The minimal legal space required for grouped gestating gilts and sows in the European Union is 1.64 m² per gilt and 2.25 m² per sow (European Commission, 2008). These recommendations apply to all group-housing systems regardless of the feeding system, the group stability or use of bedding though adjustments are made with regard to group size. For sows housed in dynamic social groups and fed by an electronic sow feeder, an available area 33% higher than the EU legal minimum was demonstrated to induce better welfare considering agonistic behaviour and consecutive wounds (Remience et al., 2008). The impact on productivity and social physiological stress was not yet determined. Nonetheless, these results may indicate that the legal minimum requirements may be insufficient for sows housed in dynamic groups and fed by electronic sow feeders. More research is needed to define the optimal space allowance, group size and pen design to prevent lameness and improve welfare of group-housed sows. In addition, recommendations should be evaluated for the different options of sow group-housing.

FLOOR CHARACTERISTICS

Flooring is one of the main features of housing that may affect lameness development in group-housed sows. Different characteristics of the floor, including the type, building material, quality, hygiene and the use of bedding may be involved.

Type

Three main floor types can be distinguished: solid, partially slatted and fully slatted floors. Housing on slatted, unbedded floors has been demonstrated to be the key risk for lameness in group-housed gestating sows. The odds of being lame for sows housed on slatted floors has been reported twice as high than on non-slatted floors (Heinonen et al., 2006), 4.6 times higher compared to solid concrete floors with deep bedding and 4.8 times higher than in sows housed outdoors (KilBride et al., 2009a). Housing sows on slatted floors during pregnancy might even lead to abnormal posture, defined as unequal weight bearing when standing, in lactating sows (KilBride et al., 2010). The reason why more sows are lame when housed on slatted floors remains unknown. The association between floor type and lameness might occur as a result of an increased prevalence of locomotor disorders or because locomotor disorders are more painful or cause more discomfort when sows walk on slatted floors. Joint diseases (osteocondrosis, arthritis) and claw lesions have been found to be the principal causes of lameness in group-housed sows (Heinonen et al., 2006; Nielsen and Haugegaard, 2012). When housed on slatted floors, pigs are provided with some challenges including chipped, sharp or worn slat edges (KilBride et al., 2009b), slipping and wedging the claws into the voids (Moultotou et al., 1999), a reduced weight bearing surface and as a consequence an increased, uneven distribution of pressure on the claws (Moultotou et al., 1999; KilBride et al., 2009b). These effects suggest that slatted floors cause lameness more likely by affecting claw health than by affecting joint soundness. This could be supported by the finding that the prevalence of joint diseases is independent from the type of floor (Jørgensen, 2003; Lahrmann et al., 2003; Scott et al., 2006). However, studies investigating the impact of floor type on joint changes have been restricted to finishing pigs and no conclusions can be drawn for group-housed sows. Even if there would be no difference in prevalence, it is still possible that sows with joint conditions encounter hard slatted surfaces more uncomfortable to walk on, resulting in an increased prevalence of clinically lame sows on slatted floors. It should be noted that most studies investigating the impact of different floor types often compare bare slatted floors with solid floors covered with straw bedding. The increased risk of lameness on slatted floors may be confounded by the lack of bedding. However, in the study by KilBride et al., 2009a, the depth of bedding in solid floored pens was not significantly associated with the prevalence of lameness, suggesting that it was the presence of slats rather than the lack of bedding that was the risk for lameness in group-housed pregnant sows. More research on the

underlying mechanism of the association between floor type and lameness in group-housed sows is needed as this is important to elaborate preventive strategies.

On economic and practical grounds, gestating sows are predominantly housed on slatted floors without bedding. To control and prevent lameness on this floor type the focus should be on building material, floor quality and hygiene.

Building material

Because it is fairly durable, cheap, resistant to wear and easy to clean, concrete is the most commonly used floor material for housing pregnant sows. Yet, in a study of Gjein and Larssen (1995b), the relative risk of lame sows on concrete slats was 2.4 times higher than on plastic slats. Claw lesions did not differ between both materials indicating that the difference in lameness may have been due to other locomotor disorders or that claw lesions may have been less painful when walking on plastic slats (Gjein and Larssen, 1995c). Plastic slats are softer and may result in less biomechanical stress to the claws and limbs compared with concrete slats (Gjein and Larssen, 1995b; Gjein and Larssen, 1995c). Hence, it may have been possible that plastic slats appeared to be more comfortable to walk on and mildly lame sows may have been missed when scoring sows on plastic slats. Though plastic slats may not necessarily be an ideal alternative for group-housing as plastic can be slippery to sows (Gjein and Larssen, 1995c). Newton et al. (1980) compared the effect of steel, plastic, concrete and aluminium slats on the occurrence of wall cracks and foot pad lesions in finishing pigs, stating that the results could be extrapolated to breeding swine. Pigs housed on concrete slats were demonstrated to have the best foot pad condition score (*i.e.* the percentage of the volar surface affected by lesions) followed by steel, plastic and aluminium slats in decreasing order of condition score. By contrast, the prevalence of wall cracks was highest when housed on concrete slats and lowest when housed on plastic and aluminium slats. Lameness was not recorded in this study and the relative importance of the lesions as a cause of lameness was not determined.

By conclusion, studies evaluating the effect of floor material on lameness development in sows are scarce. So far no clear-cut advice on building material or alternatives to concrete slats can be given to reduce the risk of lameness development in group-housed sows.

Quality

The four main quality factors contributing to a floor's total injury potential are slip-resistance, abrasiveness, surface profile and hardness (Webb and Nilsson, 1983; McKee and Dumelow, 1995). The importance of floor quality for the development of bruising, abrasions, bursitis, calluses, claw disorders and bone fractures has been extensively reported in pigs. Floors with a low slip-resistance may result in slipping and falling causing skin abrasions, bruising, bursitis, torn dewclaws and even broken bones (Blom, 1983; Webb and Nilsson, 1983; Dewey, 2006; KilBride et al., 2009b). Floors with a high abrasion level are predisposing for calluses (Leeb et al., 2001) as well as skin wounds and claw lesions (Geyer and Troxler, 1988). Especially hoof cracks have been associated with abrasive floors. Due to extensive wearing, the lateral wall horn has been demonstrated to become thinner and straightened and this mechanically worn wall horn might be more susceptible to splitting. A minimum of abrasiveness however, is necessary to prevent hoof overgrowth (Webb and Nilsson, 1983; McKee and Dumelow, 1995). Using slatted floors, also the void ratio (*i.e.* the ratio of area of holes per unit area of floor), the slot width and edge design should be taken into account. Hard surfaces (*e.g.* concrete) may lead to pressure injuries. On soft surfaces, *e.g.* soil or rubber mats, the area of contact between the claw and the floor is higher what may reduce the overloading of claws and might prevent claw lesion development (Carvalho et al., 2009). The use of mats will be described later (see 'bedding'). Finally, durability of the floor is important. A worn surface can be injurious and may interfere with its cleaning and disinfection (Kovacs and Beer, 1979). In a survey by De Belie (1997), it has been found that concrete slats could already show degradation within five years giving rise to increased surface roughness, enlarged gaps and animal injuries.

Although it is believed that these claw or limb lesions may result in clinical lameness (Webb and Nilsson, 1983), studies that have directly associated clinical lameness with floor quality have never been performed yet. Few research has been published where the effect of floor friction on the locomotion of pigs has been investigated (Applegate et al., 1988; Thorup et al., 2007a; von Wachenfelt et al., 2008; von Wachenfelt et al., 2009a; von Wachenfelt et al., 2009b). Pigs have been demonstrated to adapt their gait to potentially slippery surfaces by reducing walking speed, shortening stride length, prolonging stance time and by employing more three-limb support phases. However, when slip-resistance of the floor was too low,

adaption might no longer be sufficient to ensure safe walking. In order to prevent pigs from slipping on solid concrete floors, a floor coefficient of friction of at least 0.63 has been determined (Thorup et al., 2007a). Unfortunately, the effect on lameness development was not included in these studies.

Slip-resistance, abrasiveness, roughness and hardness may be more feasible physical floor properties to be changed on a herd compared to floor type and building material and may be suitable to implement in control and preventive strategies. Therefore, research is needed to determine the association between the quality properties of the floor and lameness in group-housed sows.

Hygiene

To prevent lameness, floors should be dry and clean. In herds with dirty, wet slatted floors, the relative risk of lame sows has been demonstrated to be 2.8 times higher than in herds with good floor hygiene (Gjein and Larssen, 1995b). The increased risk of lameness with a poor floor hygiene may be assumed to be merely claw related. An increased risk of, particularly, heel/sole erosions on dirty and wet floors has been reported for finishing pigs (Penny et al., 1963) and lactating sows (Kilbride et al., 2010). In group-housed sows, heel overgrowth seemed to be more common in herds with a bad floor hygiene and has been expected to be a chronic reaction of the heel horn (Gjein and Larssen, 1995d). Softening of the hoof horn, a higher slipperiness of the floor and the acidic caustic nature of slurry may have contributed to the increased incidence of claw lesions on wet, slurry covered floors. Furthermore, a dirty environment has been hypothesised to cause infection of claw lesions enhancing lameness (Fritschen, 1979). This theory was supported by the study of Gjein and Larssen (1995c) who reported a 4.2 times higher relative risk of claw infections for group-housed sows in herds with poor floor hygiene. Sows with claw infections are likely to be lame due to the pain induced by the inflammation.

Use of bedding

Use of solid concrete covered with deep straw bedding has been associated with a lower prevalence of lameness compared to bare solid and slatted floors (Andersen and Bøe, 1999; Scott et al., 2006; KilBride et al., 2009a; Kilbride et al., 2010). This might be explained by a reduced prevalence of locomotor disorders on deep bedding or because deep bedding appeared more comfortable to sows. Housing sows during gestation on solid concrete with straw bedding decreased the risk of heel flaps but increased the risk of toe erosions during the

subsequent lactation (Kilbride et al., 2010). Straw bedding may reduce the risk of overburdening the foot giving rise to less heel lesions. Toe erosions may be more prevalent on straw bedding, likely due to the lack of natural wearing. In the same study, the presence of toe erosions was significantly associated with unequal weight bearing while standing. No such association could be found for sows with heel flaps suggesting straw bedding in this study may have been detrimental to the sow's well-being. However, sows that are lame due to joint conditions might also develop claw lesions. Yet, in finishing pigs no significant difference in osteochondrotic joint changes have been found between deep bedded floors and bare solid or slatted floors (Jørgensen, 2003; Lahrman et al., 2003; Scott et al., 2006). The mechanism by which straw may protect group-housed sows against lameness development therefore needs further investigation.

When straw bedding is used, hygiene is important. Damp straw, soiled with faeces and urine will clearly soften the hooves, make them more prone to abrasion and pressure induced lesions and increase the risk of claw infections and hence lameness. Provision of straw has not been universally adopted as it is not compatible with slatted floors and liquid manure handling systems. In addition, it can be costly, labour demanding and may exacerbate levels of aggression between floor fed sows (Whittaker et al., 1999). Rubber mats have been suggested to be a useful and inexpensive alternative for straw bedding improving the sow's lying comfort and reducing the risk of lameness and limb lesions in group-housed sows (Tuytens et al., 2008; Elmore et al., 2010; Díaz et al., 2013). Both Elmore et al. (2010) and Díaz et al. (2013) investigated the effect of rubber mats on lameness in group-housed sows. Elmore et al. (2010) could not find a difference in lameness scores between sows housed on rubber mats versus concrete floors. However, in that study, rubber mats were only added to the feeding stalls and not to the area with concrete slatted flooring between the stalls. By contrast, Díaz et al. (2013) covered the concrete slatted flooring in both the feeding stalls and the group area with rubber slat mats. Sows housed on rubber slat mats had a significantly reduced risk of becoming lame. The reason why lameness was less prevalent on rubber may have been three-fold. Firstly, rubber is a more resilient surface compared to concrete. On rubber mats, the contact area between the claw and the floor is larger improving the claw pressure distribution and reducing overloading of claws and joints (Carvalho et al., 2009). Secondly, this cushioning effect of rubber may improve circulation in the foot (Singh et al., 1993). Standing on hard surfaces, *e.g.* bare concrete, may result in circulation problems leading to irritation of the corium of the claw. Finally, rubber slat mats may provide more traction and hence may

reduce lameness due to slipping (Webb and Nilsson, 1983; Boyle et al., 2000). Besides the potential to reduce the risk of lameness, rubber slat mats have also been associated with an increased risk of more severe toe overgrowth, heel-sole cracks, white line lesions and wall cracks (Díaz et al., 2013). More research is required to elucidate the importance of these claw lesions. In addition, the effect of rubber mats should be tested in other group-housing systems with different feeding methods, group sizes, pen designs and group stability.

1.6 Treatment and prevention of claw-related lameness

To avoid unnecessary distress and associated financial losses, early treatment and prevention of lameness is needed. The complex, multifactorial nature of lameness implies that a holistic approach will be required to control and prevent lameness in group-housed gestating sows. Because lameness is by definition a clinical sign reflecting the presence of locomotor disorders, a decision on treatment and preventive measures has to be preceded by an accurate diagnosis. Clinical examination of the lame sow may include visual assessment of the sow's gait and posture, palpation of the feet, limbs and back and swabbing or sampling affected joints. However, clinical examination can be difficult and in addition, necropsy or medical imaging techniques may be required to make the final diagnosis. About 5 to 20 per cent of lameness cases in breeding sows are reported to be attributable to foot lesions (Dewey et al., 1993; Kirk et al., 2005). Location (Anil et al., 2007; Anil et al., 2008b) and severity (Gjein and Larssen, 1995b; Pluym et al., 2011) of the claw lesions might determine whether a sow will show overt lameness or not. Additionally, claw lesions may permit entry of infection that might spread upwards, affecting joints and other tissues (Penny et al., 1965). As such, infected claw lesions can be even more a causative factor of lameness (Gjein and Larssen, 1995b). In this introduction, treatment and prevention of claw-related lameness in group-housed sows will be described.

1.6.1 TREATMENT

First of all, the question should be raised whether the animal warrants treatment. Infected claw lesions and arthritis are mainly detected in the chronic stage and prognosis is often poor. Therefore, the first step will be the decision on whether the animal can be cured, or whether

culling or euthanasia is preferred (Rowles, 2001). Post-mortem investigation of these culled and euthanized sows can yield additional diagnostic information.

Because lame sows may suffer from severe pain, from a welfare point of view, animals need to be treated with a non-steroidal anti-inflammatory drug (NSAID). Oral administration of ketoprofen at a dose of 2mg/kg for five consecutive days (Mustonen et al., 2011) or injection with meloxicam at a dose of 0.4mg/kg for two consecutive days (Friton et al., 2002) have been proven to be efficacious and safe for treatment of non-infectious locomotor disorders in pigs.

Treatment of infected claw lesions is most challenging because of the difficulty in ensuring adequate local treatment. Ideally, infected lesions should be cleaned, debrided and disinfected followed by an antibiotic (topical and general) and NSAID therapy (Martineau and Morvan, 2010). Penicillin is commonly recommended (Cowart and Casteel, 2001; Rowles, 2001). Due to its good tissue distribution, with high concentrations at the level of the bones and joints, lincomycin has been advised in treatment of deep infections, such as laminitis and arthritis, with anaerobes and Gram-positive bacteria. However, in view of the concerns about antimicrobial resistance and the well-considered usage of antibiotics, the choice of an appropriate antibiotic should be based on the results of sensitivity tests to determine antimicrobial susceptibility of the causative pathogen(s). A variety of organisms may be involved depending on the type of infected claw lesion. Gram-positive cocci were the main organisms isolated from claw erosions and white line lesions. *Fusobacterium necrophorum*, *Trueperella pyogenes* and spirochete species were isolated from false sand-cracks (*i.e.* vertical wall cracks starting from the white line) and foot-rot lesions (Penny et al., 1963; Jackson and Cockcroft, 2007). Foot-rot (bush foot, bumble foot) is a problem of pedal sepsis with infection of soft tissue and occasionally bone that may break through at the coronary band (Jackson and Cockcroft, 2007). In non-responsive cases, amputation of the claw can be considered (Cowart and Casteel, 2001; Jackson and Cockcroft, 2007).

Claw trimming in case of digital overgrowth is necessary as overgrown claws have been associated with lameness (Jørgensen, 2000). Even in sows that do not show lameness, trimming of overgrown digits is recommended as overgrown toes may get infected over time (Jackson and Cockcroft, 2007) and long dew claws can get stuck in the slots of slatted floors and may be ripped off, which is very painful for the animal (Jackson and Cockcroft, 2007). Claw trimming has also been reported as part of the treatment strategy of pododermatitis

(Martineau and Morvan, 2010) and laminitis (Guimaraes et al., 2008). It is noteworthy that claw trimming in swine may be harder compared to claw trimming in cows because of the larger difference in height between medial and lateral claws and the much thinner sole horn (van der Meulen et al., 1990; Kroneman et al., 1992).

The use of foot baths as part of a treatment strategy was described by Penny et al. (1965). In this study, outbreaks of foot-rot due to infected false sand-cracks were treated successfully by the twice-weekly use of a foot bath containing five to ten per cent formalin solution.

1.6.2 PREVENTION

Because treatment of claw-related lameness is frequently awkward or unrewarding, there is merit in working towards prevention and management. Since 2013, group-housing of gestating sows is obligatory in all member states of the European Union. Several authors have already reported a higher prevalence or incidence of claw lesions in group-housed sows compared to individually stalled sows (de Koning et al., 1990; van der Meulen et al., 1990; Gjein and Larssen, 1995c; Gjein and Larssen, 1995d; Anil et al., 2007). Therefore, knowledge on possible strategies to control and prevent development of claw lesions in loose housed sows is of major importance. Factors affecting the prevalence and severity of claw lesions and infections are related to claw conformation, housing, nutrition and management. They are the key to reduce lameness caused by claw lesions.

CLAW CONFORMATION

Genetic selection may be part of the preventive strategy. Claw lesions are more prevalent and/or severe on lateral claws than on medial claws (Kornegay et al., 1990; van der Meulen et al., 1990; Gjein and Larssen, 1995d; Mouttotou et al., 1999; Anil et al., 2007; Bradley et al., 2009; van Amstel and Doherty, 2010). Inequality of the size of the claws and varying tissue strength between medial and lateral claws contribute to the difference in susceptibility (Penny et al., 1963; Webb, 1984; Tubbs, 1988; Kroneman et al., 1993b). Lateral claws are larger than medial claws. The discrepancy in size is more pronounced on rear feet than on front feet and increases as pigs age (Penny et al., 1963; Bradley et al., 2009; van Amstel and Doherty, 2010). As the difference in size between lateral and medial claws becomes larger, the frequency of claw lesions increases (Kornegay et al., 1990). Claw size discrepancy has been

significantly associated with a higher culling risk (Tarrés et al., 2006). Disparity in claw size is hereditary. A wide range of heritability values, depending on breed and statistical method, has been reported, varying from 0.01 to 0.61. (Van Steenbergen, 1989; Jørgensen and Vestergaard, 1990; Jørgensen and Andersen, 2000; Luther et al., 2007; Fan et al., 2009b). Recently, Fan et al. (2009a) identified possible genetic markers associated with uneven claw size. Hence, it should be investigated whether genetic selection of replacement gilts with even-sized toes may help to control the development of claw lesions. De Sevilla et al. (2008) found that leg conformation may evolve over the productive life of a sow. Therefore, preference probably should incline towards genetic selection instead of phenotypic selection at the end of the rearing period. Similarly to claw size asymmetry, abnormal hoof growth has been associated with an increased culling risk in sows and has been reported to be moderately heritable, in the range 0.24 – 0.38 (Quintanilla et al., 2006; de Sevilla et al., 2008; de Sevilla et al., 2009a; de Sevilla et al., 2009b). Due to its relevant genetic background and the impact on sow culling, hoof growth could also be an appealing selection criterion for prevention of claw lesions and improvement of sow longevity.

HOUSING - FLOORING

Flooring is one of the main features of housing that may affect the development of claw-related lameness in group-housed sows. It was previously described in the section on risk factors of this introduction. Relevant studies from 1990 specifically investigating the impact of flooring on claw lesion development are listed in table 4. Based on all this information, the preventive measures that can be taken to prevent claw-related lameness, are defined.

Group-housing on deep litter based on straw, appeared to be the best solution to reduce the incidence and severity of claw lesions and lameness. The greater the straw allocation used, the lower the increase in claw lesions during gestation (Olsson and Svendsen, 2004). The positive effect of deep bedding systems is apparent, but does not guarantee full protection against claw lesions. Straw may reduce the risk of overburdening the foot but, unless the upper layer of the straw bedding is kept fresh and dry, the horn will decrease in strength and become prone to lesions. The lack of wear in the straw-bedded lying area can be compensated by use of a non-bedded dunging area. To prevent development of claw lesions, the dunging area must be kept as dry as possible (use of slatted floors or a scraper). Use of a pitch of the solid floor towards the dunging area, may help to drain urine (Altena et al., 2004).

Table 4: Contributions since 1990 to the study of the impact of flooring on development of claw lesions in (group-housed) sows

Reference	Contribution
Kornegay et al. (1990)	Concrete floors are a major risk factor for claw lesions in young gilts
de Koning et al. (1990)	Quality of the floor influences the development of claw lesions
van der Meulen et al. (1990)	Concrete slats are a risk factor for lameness and claw lesions
van Beers-Schreurs et al. (1991)	The longer sows are kept on slatted floors, the higher the prevalence of claw lesions
Kroneman et al. (1992)	Review of claw health in pigs and floor as risk factor for claw disorders
Svendsen et al. (1992)	Slatted floors are a risk for claw lesions, bedding may be a solution
van der Wilt et al. (1992)	Group-housing of sows on partly slatted floors without bedding is associated with claw lesions and lameness
Kroneman et al. (1993b)	Review of the risk factors associated with claw lesions and lameness
Gjein and Larssen (1995d)	Floor quality and hygiene play an important role in development of claw lesions.
Gjein and Larssen (1995c)	Group-housing on slatted floors is a high risk for claw lesions in sows; lowest prevalence in group-housed sows on deep litter
Gjein and Larssen (1995b)	Dirty floors, little space and concrete slats are risk factors for lameness and claw infections in pregnant sows
Backus et al. (1997)	Use of trickle feeding and ESF related to the highest prevalence of foot lesions in sows
Holmgren et al. (2000)	Claw health in group-housed sows better on straw
Barnett et al. (2000)	Review of flooring as a risk factor for claw lesions in sows
Ehlorsson et al. (2002)	Use of straw bedding associated with higher risk of overgrown hooves
Olsson and Svendsen (2002)	No difference in claw injury between solid concrete or partially slatted with concrete or plastic slats.
Altena et al. (2004)	Quality and hygiene of straw important to prevent claw lesions
Olson and Svendsen (2004)	Size of a straw bedding ration is has a positive effect on claw health
Norring et al. (2006)	No effect of coating concrete floors on claw lesions in lactating sows
Kilbride et al. (2009b)	Slatted floors during pregnancy increase the risk of heel flaps and abnormal posture in lactating sows. Deep bedding and bad quality of slats increase the risk of toe erosion
Kilbride et al. (2010)	

In litterless housing systems, the floor quality and hygiene are of paramount importance to control and prevent development of claw lesions (Kovacs and Beer, 1979; McKee and Dumelow, 1995). Slip-resistance, abrasiveness, hardness and surface profile are the main characteristics contributing to the injury potential of a floor. If the optimum level of each characteristic is met, injuries may be minimal (McKee and Dumelow, 1995). Webb and Nilsson (1983) and Kovacs and Beer (1979) described different methods by which the physical floor properties can be measured, as well as some standards that should be met to be suitable for pig housing. Using slatted floors, also the void ratio (i.e. the ratio of area of holes per unit area of floor), the slot width and edge design should be taken into account. Webb (1984) defined an equation, based on pig's live weight, to derive the maximum safe void percentage. For sows, this would suggest a maximum void percentage of 50%. Concrete slatted floors used for sow housing have a maximum void percentage of 20% and therefore are safe. Triangular metal slats have a void close to 50%. Sows can tolerate this type of flooring but their soft heel bulb tissue starts to come under increasing stress and this may induce pain and discomfort (Webb, 1984). In 1988, Tubbs suggested that smooth, well-crowned slats with 1.3 to 1.6 cm slat openings would minimize claw lesions whereas 1.9 to 2.5 cm slat openings increased the risk of sows' toes and dewclaws becoming entrapped. This recommendation is smaller than the maximum slot width of 2.0 cm imposed by the Council Directive of 2008 (2008/120/CE). However, all of these studies were performed almost thirty years ago, whereas housing and flooring for pigs, as well as sow genetics, have been revolutionized over the past decades. No standards regarding floor characteristics for group-housed sows could be found and it is apparent that results from different measurement devices are not comparable (Webb and Nilsson, 1983). Hence, more contemporary studies are necessary to determine standards for slip-resistance, abrasiveness, hardness and void ratio required to minimize lesions in group-housed sows. Accurate measurement devices and well-defined lesion scoring systems are necessary to ensure results from future studies would be comparable.

The wear resistance and age of the floor is important as well. The feeding method appeared to play a prominent role in speed of concrete attack through formation of an acidifying mixture between feed and water (De Belie, 1997). The closer the water and feed supply, the faster the attack proceeded, with the use of liquid feed significantly associated with worst degradation. Placing a bin underneath the drinking nipple or protection of the concrete surface by a top layer with portland cement or "product S", based on ground tuff, diminished concrete attack.

Coatings (e. g. epoxy) can be used but seem to have a much shorter life, i.e. only a few years. To prevent development of infected claw lesions and associated lameness, floors should be as dry and clean as possible (Webb, 1984; Tubbs, 1988; Kroneman et al., 1993b; Gjein and Larssen, 1995b; Gjein and Larssen, 1995d). Old, rough floors may be harder to clean and therefore are more likely to harbour bacterial organisms (Tubbs, 1988). Hence, sufficient and regular cleaning is a prominent part of claw lesion prevention. In the study of De Belie (1997), high-pressure cleaning did not affect concrete degradation and use of cleaners even seemed to delay degradation.

NUTRITION

Knowledge of the optimum feeding strategy and nutrient requirements for sows with prevention of claw lesions in mind is limited. Recent studies, since 1990, are listed in table 5.

Table 5: Contributions since 1990 to the study of the impact of nutrition on claw health of (group-housed) sows

Reference	Contribution
Mensink et al. (1990)	Haemorrhagic claw lesions in piglets due to Se toxicosis during pregnancy of the sow.
Greer et al. (1991)	Biotin supplementation reduces the incidence of claw lesions in gilts and sows.
Watkins et al. (1991)	Biotin supplementation do not affect foot health and structural soundness in gilts and sows
Kroneman et al. (1992)	Review of nutrition as risk factor for claw disorders
Kim and Mahan (2001)	Feeding >7ppm inorganic Se to sows during lactation leads to hoof separation and alopecia in piglets
van Barneveld and Vandeppeer (2008)	The role of nutrition in sow foot health
Anil et al. (2009c)	Supplementation of trace minerals (Cu, Zn, Mn) reduces incidence of claw lesions in group-housed sows
Anil (2011)	Supplementation with complexed trace minerals (Cu, Zn, Mn) reduces severity of claw lesions in group housed sows
van Riet et al. (2013)	Review on the impact of nutrition on claw health in sows

Van Barneveld and Vandeppeer (2008) and van Riet et al. (2013) reviewed the role of nutrition in sow foot health. The main nutrients affecting claw health in pigs, as reported by these authors, include fatty acids, the amino acids cysteine and methionine, the minerals calcium, zinc, copper, selenium, manganese and chromium, and vitamins A, D, E and biotin. Only the effect of biotin has been extensively investigated (Brooks et al., 1977; Grandhi and Strain, 1980; Penny et al., 1980; Money and Laughton, 1981; De Jong and Sytsema, 1983; Hamilton and Veum, 1984; Webb et al., 1984; Bryant et al., 1985a; Bryant et al., 1985b; Kornegay, 1986; Misir and Blair, 1986; Simmins and Brooks, 1988; Greer et al., 1991; Watkins et al., 1991). However, studies disagree on the beneficial effect of biotin supplementation to growing gilts or adult sows. Inconsistency may be due to variation in biotin concentration of the basal diet, supplemented biotin level, duration of supplementation, bioavailability of biotin and variation in management, housing and genetics, which may also affect claw health. Although still no clear conclusions can be drawn, studies on biotin stopped at the beginning of the nineties and supplementation of biotin is yet considered important (G.-P. Martineau, Personal communication, March 17, 2013). The dietary energy, calcium and phosphorus level fed to developing gilts has little to no effect on the incidence and severity of claw lesions during rearing or later in life (Kornegay and Thomas, 1981; Calabotta et al., 1982; Arthur et al., 1983). These studies are rather old and research is needed to investigate whether these studies are still relevant in today's sow management. In 1985, Lepine et al. could not find an effect of feeding elevated vitamin-mineral levels (150% of daily recommendation) on the incidence and severity of claw lesions in boars. However, recent studies on group-housed sows reported that supplementation of trace minerals (Zn, Cu and Mn) may reduce both the incidence of claw lesions (Anil et al., 2009c) and severity of vertical claw cracks (Anil, 2011) with an improved effect of supplementing amino acid complexes instead of inorganic trace minerals. Nutrient requirements currently recommended for gestating or lactating sows are based on growth and reproductive performance. Van Barneveld and Vandeppeer (2008) hypothesized that the vitamin and mineral requirement level to maintain optimum foot health may be higher than that required for optimum growth and reproductive performance. However, as research is lacking or inconsistent, it is difficult, if not impossible, to state whether supplementation of vitamins and minerals above the currently recommended level is beneficial for either developing gilts or group-housed sows.

MANAGEMENT

Routine hoof trimming once or twice a year has been well established in dairy herds. It improves claw health and even may increase the functional life of a dairy cow by one lactation (Ishler and Wolfgang, 1999). In sows, however, claw trimming is not applied on a regular basis. According to van der Meulen (1990) and Kroneman et al. (1992), claw trimming in sows may also be harder than in cows. Although older studies suggest routine claw trimming in pigs is necessary (Kroneman et al., 1992), more recent studies do not recommend claw trimming as a prophylactic measure in group-housed sows. The lack of improved longevity and the absence of a clear effect on claw lesion development do not justify the additional labour and costs associated with regular, preventive claw trimming (Ehlorsson et al., 2003; Vestergaard et al., 2006; Spoolder et al., 2009).

The use of foot baths for pigs has been advocated both for treatment and prevention (Penny et al., 1965; Powe, 1976; Bilkei, 1989). However, available studies are dated and there is a lack of recent controlled studies conducted on group-housed sows under field conditions. Products suggested for use in foot baths are copper sulphate, zinc sulphate and formalin (Penny et al., 1965; Powe, 1976; Bilkei, 1989). Due to environmental concerns, the use of copper and zinc sulphate should be avoided. Formalin can be used but because of many human health concerns, not least of which is its status as known carcinogen, usage of formalin may be prohibited in the near future. Glutaraldehyde and quaternary ammonium compounds could be possible alternatives. As sows may be attracted to lay down in, or drink from, the foot bath, mats impregnated with disinfectants, might be safer. However, to our knowledge, there is no recent refereed scientific literature evaluating the use of foot baths or mats, or different disinfectant products, to prevent claw lesions in group-housed sows.

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To avoid unnecessary distress and financial loss, control and prevention of sow lameness is needed. Reliable prevention of lameness requires first accurate detection methods. Visual assessment is the most commonly used approach to detect lameness in (farm)animals. However, visual scoring systems are subjective, prone to observer error and often fail to detect slightly lame sows. More objective, precise and sensitive lameness detection techniques based on kinematics and kinetics have already been successfully used in horses, cattle and poultry, but not yet in sows. Secondly, working towards a reduction in sow lameness requires motivation of the farmer. Understanding the implications of lameness may be important. Although the indirect effect of lameness has been extensively described, the direct impact on the sow's reproductive performance remains subject of discussion. A final requirement critical for the development of preventive strategies is to identify risk factors for lameness. The multifactorial nature of the condition in which sow, housing and management related factors are involved, implies that a holistic approach is needed to control and prevent sow lameness.

The general aim of this thesis was to improve control and prevention of lameness in group-housed gestating sows.

The specific objectives were:

- ▶ To improve objectivity, precision and sensitivity of lameness detection by developing a detection method based on balance analysis and image processing,
- ▶ To elucidate the direct impact of lameness on the sow's reproductive performance,
- ▶ To determine the stage in the reproductive cycle at which lameness is most prevalent,
- ▶ To investigate risk factors for lameness at herd level in commercial pig herds.

A schematic representation of the different parts of this thesis is shown in fig.1.

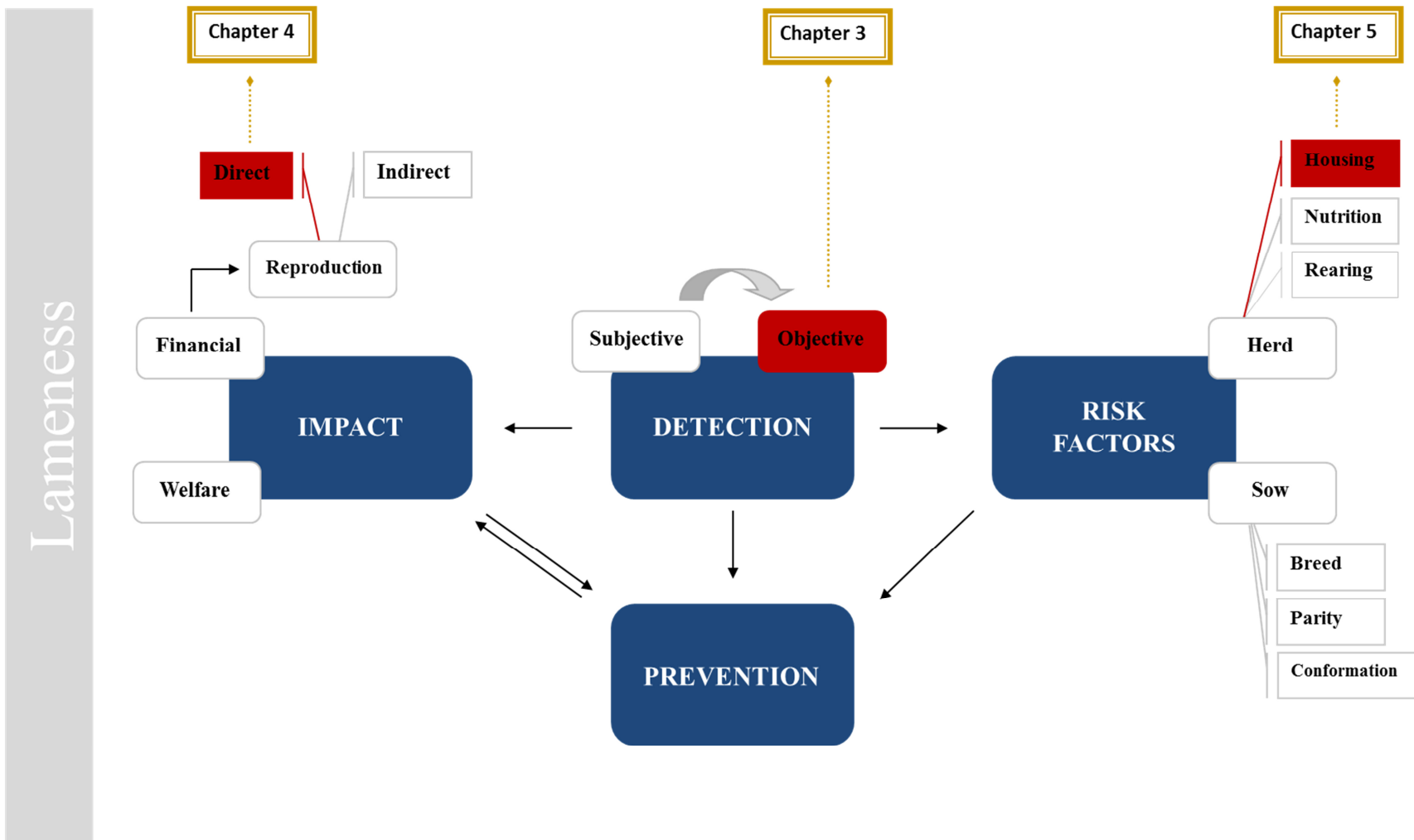


Fig. 1. Schematic representation of the different parts of this thesis

Development of a system for objective lameness detection in sows: SowSISⁱ

3.1 Abstract

Lameness in sows is an important welfare concern as well as a cause of considerable economic loss. In general, lameness in sows is evaluated by visual scoring of the gait. However, visual assessment is a subjective technique with low reproducibility. Therefore, the need arises for more accurate and objective methods to enable correct detection. A detection system, based on force stance variables derived from balance analysis and visual stance variables derived from image processing was developed: SowSIS (Sow Stance Information System). The transportable device and computer software was tested in a practical environment and was positively evaluated for its practical use and precise measurements. A proof-of-concept study of the force stance variables was performed by comparing measurements of sound sows and sows with lameness in their hind leg. All lame sows were reluctant to bear weight on their lame leg which resulted in a lower weight exerted by the lame hind leg compared to the other legs. This shift in weight was mainly compensated by putting more weight on the contra-lateral sound hind leg. Sows showed more but shorter kicks (*i.e.* lifting leg of the ground) with their lame leg compared to the other legs. The results indicated that the developed system SowSIS has very promising potential to support future objective research in lameness in sows.

ⁱ **Adapted from:** Pluym L. M., Maes D., Vangeyte J., Mertens K., Baert J., Van Weyenberg S., Millet S. and Van Nuffel A. (2013). Development of a system for automatic measurements of force and visual stance variables for objective lameness detection in sows: SowSIS. *Biosystems Engineering* 116, 64-74.

3.2 Introduction

Lameness is one of the leading emerging disease conditions in swine breeding herds. Due to pain and suffering, lameness is recognized as an important welfare concern (Farm Animal Welfare Council, 1992; Whay et al., 2003). Furthermore, lameness causes considerable economic losses as a result of additional labour, repeated treatments, euthanasia, early culling (Dewey et al., 1992; Jørgensen, 1999; Rowles, 2001; Stalder et al., 2004; USDA, 2013), and (re)production losses (Schuttert, 2008; Anil et al., 2009). Schuttert (2008) calculated a loss of 20-30 euro per sow present in the herd and Deen et al. (2008) reported costs of up to US\$180 per lame sow. The estimated prevalence of lameness in sows differs between studies and countries, and reported values range from 8% to 15% (Gjein and Larssen, 1995a; Bonde et al., 2004; Heinonen et al., 2006; Kilbride et al., 2009; Pluym et al., 2011). Since January 1, 2013, it has been obliged in the EU member states to house gestating sows in group (European Commission, 2008). Because the prevalence of sow lameness was found to be higher in group-housed sows compared to sows kept in stalls (Backus et al., 1997; Estienne et al., 2006; Chapinal et al., 2010b) a further increase of lameness problems was expected (Kroneman et al., 1993; Anil et al., 2005; Estienne et al., 2006; de Sevilla et al., 2008).

To control financial losses and welfare problems, early and accurate detection and hence, early treatment of lameness is essential. Generally, detection is performed by visually scoring the gait and/or posture. Visual assessment is inexpensive and easy to perform, but is also prone to observer error mainly due to limitations of human visual perception (Krebs et al., 1985; Main et al., 2000; Petersen et al., 2004; Tiranti and Morrison, 2006; Fan et al., 2009). Moreover, sows that are severely lame are easily detected but mild lameness cases may remain unidentified. Increasing herd size and housing pregnant sows in groups will likely further impede sufficient monitoring of the individual sow by the farmer (Estienne et al., 2006; Cornou et al., 2008; Chapinal et al., 2010). Therefore, automated and objective assessment will become crucial to enable early and accurate detection.

Over the last decade, automatic lameness detection has been investigated in other animal species. Several walk over or posture measurement techniques have been used to objectively quantify gait and stance variables. These techniques all rely on the assumption that animals will be less willing to exert force on the affected leg (Keegan et al., 1998; Corr et al., 2003). Spatial and/or temporal variables, but also force related variables, were successful in lameness evaluation in dogs (Quinn et al., 2007), horses (Bertone, 2003; Weishaupt et al., 2006), cows

(Tasch and Rajkondawar, 2004; Flower et al., 2005; Telezhenko and Bergsten, 2005; Van der Tol et al., 2005; Pastell et al., 2006; Pastell et al., 2008; Maertens et al., 2011) and chickens (Corr et al., 2003). In pigs, research on automatic lameness detection has been performed by Thorup et al. (2007), von Wachenfelt et al. (2009a), and von Wachenfelt et al. (2009b). Both research groups used force plates to biomechanically evaluate the gait of pigs in relation to floor properties. While these experiments yielded interesting results, the natural stilted locomotion of sows, their instinct to suppress clinical signs of lameness and the inability to lead a sow while walking, still make detection very difficult. Therefore, a system based on stance variables seems more practical and feasible for lameness detection in pigs. Indeed, Sun et al. (2011) recently reported the possible use of force plates to detect lameness during stance in sows.

Feet and leg soundness and therefore sow longevity may be linked not only with the weight distribution between legs during stance, but also with leg conformation (de Sevilla et al., 2008; de Sevilla et al., 2009). Conformation traits are low to moderately heritable and hence, could be taken into account when selecting gilts (Serenius et al., 2001; Tarrés et al., 2006; de Sevilla et al., 2008; de Sevilla et al., 2009). Therefore, evaluation of standing posture in relation to feet and leg soundness was included in several visual scoring methods (Main et al., 2000; Kaler et al., 2009). Regarding subjectivity of visual assessment, more objective tools are also needed to evaluate sow posture.

The aims of this study were (1) to develop a device that measures weight distribution between the four legs of sows and that provides lateral digital images from the hind legs; (2) to derive and test the repeatability of different stance variables from balance analysis and from image analysis that are relevant for lameness research, and (3) to perform a proof-of-concept study to investigate whether force stance variables differ significantly between clinically lame and sound sows in practical settings. It was hypothesized that a practical system can be built by which stance variables can be measured with sufficient repeatability and that force stance variables significantly differ between clinically lame and sound sows. Visual stance variables will be the subject of future research.

3.3 Materials and methods

3.3.1 THE RATIONALE FOR THE CHOICE OF METHOD

Although a variety of effective kinematic- and kinetic-based techniques are available for gait and posture analysis (subchapter 1.4.2), preference was given to static examination based on balance and image analysis. In view of the specific application in pigs and pig herds, measurements while standing have several advantages over dynamic lameness examination. First, static lameness examination does not involve the steady walking speed that is required for dynamic examination as fluctuations in speed attribute to variability in kinematic variables (Herlin and Drevemo, 1997; Khumsap et al., 2002) and ground reaction forces (Corr et al., 2003; Oosterlinck et al., 2010). The locomotion of pigs is difficult to control and pigs naturally respond with a short fast advancement instead of a steady pace when urged to move (Main et al., 2000). Calabotta et al. (1982) and von Wachenfelt et al. (2008) performed dynamic gait analyses in pigs and both reported that it was hard to maintain a continuous normal relaxed gait as many of them jumped or ceased walking. Measuring the load distribution when the animal is standing therefore certainly is an advantage for pigs. Secondly, lameness examination when animals are standing is easier to implement on farm. Video-based kinematic analysis (e.g. marker-based cinematography) has been reported to be successful in quantifying sow gait and lameness (Grégoire et al., 2013). Yet, it is time-consuming and the complicated set-up and expensive equipment restrict the use of video-based gait analysis to research settings. Owing to the size of force plates, many passages may be needed to record a sufficient number of valid strides which is time-consuming and increases variability in the data (Corr et al., 2007). A treadmill could offer a solution and was used in pigs by Calabotta et al. (1982) and Barczewski et al. (1990). Yet, treadmill locomotion may differ from overground locomotion (Buchner et al., 1994; Herbin et al., 2007). Finally, static measurements are usually less expensive than dynamic systems. When standing, information on the vertical component of the ground reaction force provided by basic force plates is sufficient. Hence, static lameness examination does not necessitate the multicomponent force plates as used for dynamic examinations reducing the price and increasing on-farm suitability. As the goal was to develop a method also feasible to be used on-farm, preference inclined towards measuring the limb load distribution while sows are standing.

3.3.2 DEVELOPMENT OF THE MEASUREMENT SYSTEM

The measurement system SowSIS (Sow Stance Information System) consisted of an aluminium box (2.06 m long x 0.79 m width x 1.11 m high) and was constructed to be a transportable walk-through device. It consisted of seven dismantable parts (Fig 1): two side wall panels, one front panel and one hind panel, a top panel, a bottom plate and a rotatable arm. In both side wall panels, the aluminium plates could be shifted upwards so that the leg could be visible for the camera from toe to knee (Fig. 1). The front panel was designed as a door with double wire mesh allowing for straw or other enrichment material to be inserted. The hind panel was lockable to restrain the sows during measurements. The two main measuring systems were incorporated in the bottom plate (a platform with four balances) and the rotatable arm with a camera.

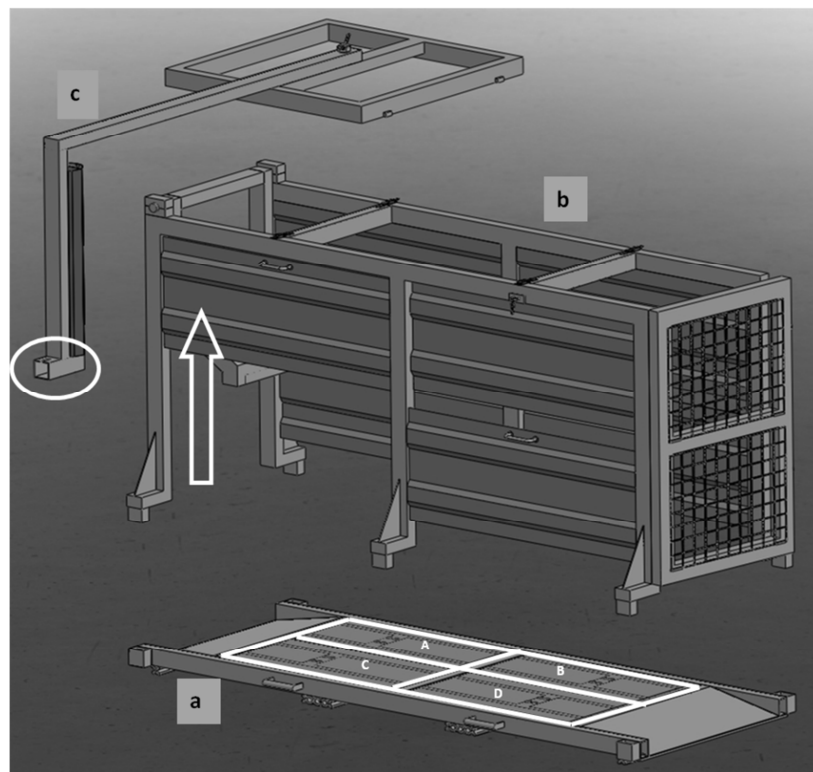


Fig. 1. The measurement device SowSIS. The device consists of (a) the bottom plate containing four balances (A-B-C and D), (b) the central box with a double wire mesh front panel used as door, and (c) the arm with camera (white circle) and fluorescent tube above the camera (c). On this drawing, the aluminium plate at the right side at the rear is shifted upwards (white arrow).

FORCE MEASUREMENTS BASED ON THE PLATFORM WITH FOUR BALANCES

Set up. The bottom plate was divided in four equal quadrants each designed as a balance. The hammered aluminium top plate of each balance measured 0.64 m x 0.29 m and was connected to an aluminium single point load cell (AP 635, SCAIME™, France) which was attached to the bottom structure of the box. The size of the hammered top plates was determined after carefully measuring leg positions in sows of different size/age in individual stalls. Dimensions of the plate and the box were designed to prevent the sows simultaneously standing on one plate with two feet. Figure 1 shows the installation of the four balances with load cells in the measurement box.

The analogue voltage output of all four load cells was sampled differentially at 250 kHz with a 16 bit NI USB 6211 card (National Instruments, Austin Texas, USA) that was mounted in a tablet PC (Getac E100, Getac Inc., California, USA). The digitalized output of the load cells was then transformed to actual load exerted by the sow on the balances by application of a LabView program (National Instruments, Austin Texas, USA) based on the linear equations from the calibration of each balance. The LabView program visualised the weights during measurements making it possible to monitor the measurement in real time. Special care was taken to keep all electronic devices portable and outside of the measurement box.

Platform calibration. Balances were calibrated using reference masses ranging from 5 kg to 175 kg. The output of each load cell was plotted on a graph to test linearity between the certified reference mass (kg) and the output of the load cells (mV) which were now incorporated in the balances. This resulted in four linear equations that were further used in the LabView program to calculate the loads exerted on the balances. All linear regression coefficients (R^2) of these equations were approximately 1 (0.99999 ± 0.00001). This confirms the correct functioning of the load cells when incorporated in the balances. To test whether position influenced balances measurements, reference masses were subsequently placed on one the four corners of each top plate. To test for drift, a reference mass of 50 kg was placed upon the top plates for 30 minutes. Drift is defined as the actual change in the measurement value when the same (reference) mass is measured under the same conditions, same operator, at different points in time. The coefficient of variation (CV) was calculated over the four positions and over time.

Measurements. Balance measurements started after the sow had entered the measurement box and lasted at least 5 min at 10 Hz (total of 3000 measuring points).

ROTATABLE ARM WITH DIGITAL CAMERA SYSTEM

Set up. A rotatable aluminium arm was fixed on top of the measurement box (Fig. 1). At the end point of the vertical section of the arm, an AVT Guppy F-080C digital colour camera (Allied Vision Technology GmbH, Stadtroda, Germany) was fixed approximately 0.365 m above the ground at a horizontal distance of 0.960 m from the device. The camera was equipped with a 6 mm lens (DF6HA-B1, Fujinon GmbH, Germany) and was focused on the hind leg of the sow from toe to hip. The camera was triggered externally and a FireWire 400 cable connected the camera with the tablet PC. Images were acquired using AVT SmartView 2 v.11 (Allied Vision Technology GmbH, Stadtroda, Germany). A fluorescent tube was fixed to the vertical section of the arm above the camera at the side of the box, serving as an additional light source (Fig. 1).

Measurements. While the sow was standing in the device, a lateral view of the left and right hind leg was taken with the digital camera. First, the position of the stifle joint, the tibiotarsal joint and the middle of the region of the metatarsophalangeal joint and the coronary band viewed from the lateral side were marked on the sows with a wax-based marker (Fig. 2). The rear side panel was then slid upwards so the lateral side of the hind leg was visible. After taking the first picture, the side panel was slid downwards again and the same protocol was followed at the other side. Marks on the measurement box were used to ensure a standard position of the camera.

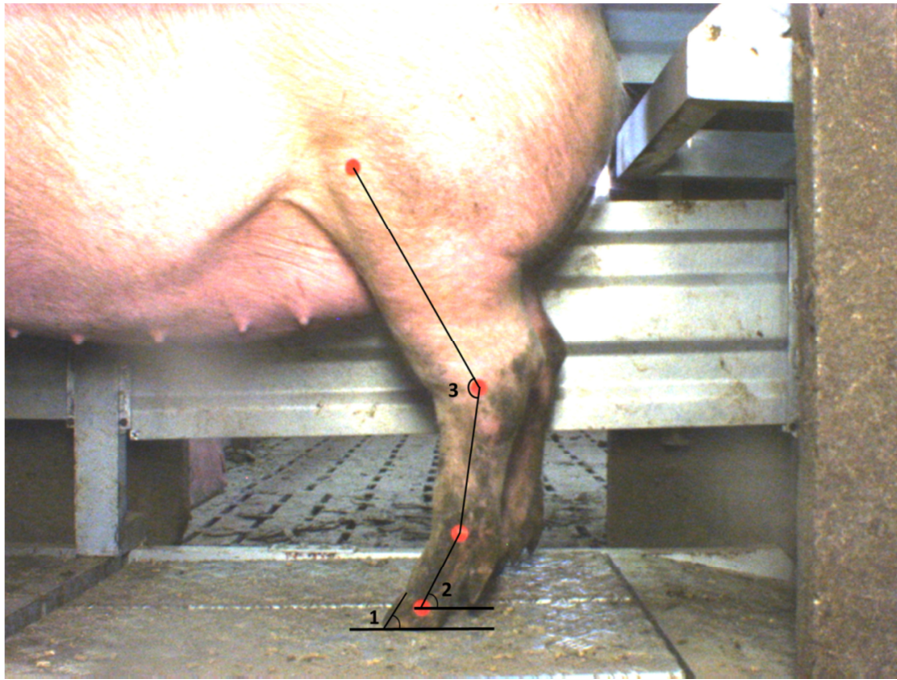


Fig. 2. Representation of the three visual stance variables (angle of the claw (1), axis of the long pastern bone (2) and angle of the hock (3)) on a digital image from the lateral view of the left hind leg of a sow.

3.3.3 SELECTION AND CALCULATION OF VARIABLES

VARIABLES FROM BALANCE MEASUREMENTS

Raw data processing from the *.txt file was automated in Matlab 7.13 (R2011b, MathWorks Inc, Natick, USA). The first step in processing the raw data was to delete erroneous data caused by sows that did not stand correctly on the balances or leaned against a side panel. The operation of the program to delete erroneous data was a modified version of the method used in cow lameness research (Pastell et al., 2008). The program subtracted the total weight exerted by the four legs at each measuring point from the mean total weight over the whole measurement period. If the difference was over 20 kg, then the measuring point was deleted. The threshold of 20 kg was based on and adjusted according to Pastel et al. (2008) and the effect of changing the correction limit on the relevant data content and the number of kicks was visually evaluated in Fig. 3. Thresholds below 20 kg caused exclusion of more than 10% of the raw data. The number of kicks remained approximately equal until the threshold was lower than 20 kg (Fig. 3), hence a threshold for deleting erroneous data was set at 20 kg. After eliminating erroneous data, different force stance variables relevant for lameness

characterisation were calculated (Table 1). The mean absolute and mean relative weight for each leg over the entire measurement period of 5 min was calculated as well as the relative weight for front, hind, left and right side. In addition, the leg weight symmetry (ratio of the absolute weight of two legs) was determined. Besides these variables kicks (number and duration) and weight shifts (number, duration and magnitude) were measured based on the promising results in cow lameness research. Definitions of kicks and weight shifts are described in Table 1 and illustrated in Fig. 4. The thresholds to detect kicks and weight shifts were based on Pastel et al. (2008) but recalculated for the body mass of sows. In Fig. 5a applying a threshold of 10 kg supports this decision as the number of kicks stagnated at this threshold. Regarding the number of weight shifts, a continuous decrease can be seen in Fig 4b when increasing the threshold. Therefore, to include as many weight shifts as possible and to make sure that the sows did indeed shift weight between two or more legs, the threshold was set at 10 kg. This was supported by the visual interpretation of the sows' standing behaviour during measurements.

The maximum and minimum values, standard deviation (SD) and coefficient of variation ($CV = SD/\text{mean}$) over all measuring points during the whole measurement period (5 min) were calculated for each variable.

VARIABLES FROM CAMERA SYSTEM

To obtain an objective representation of the posture of the sow, the angle of the claw, the axis of the long pastern bone and the angle of the hock were calculated from the digital images from the lateral view of both hind legs using an image manipulation program (GIMP 2.6). Definitions of the three visual stance variables are described in Table 1 and Fig. 2.

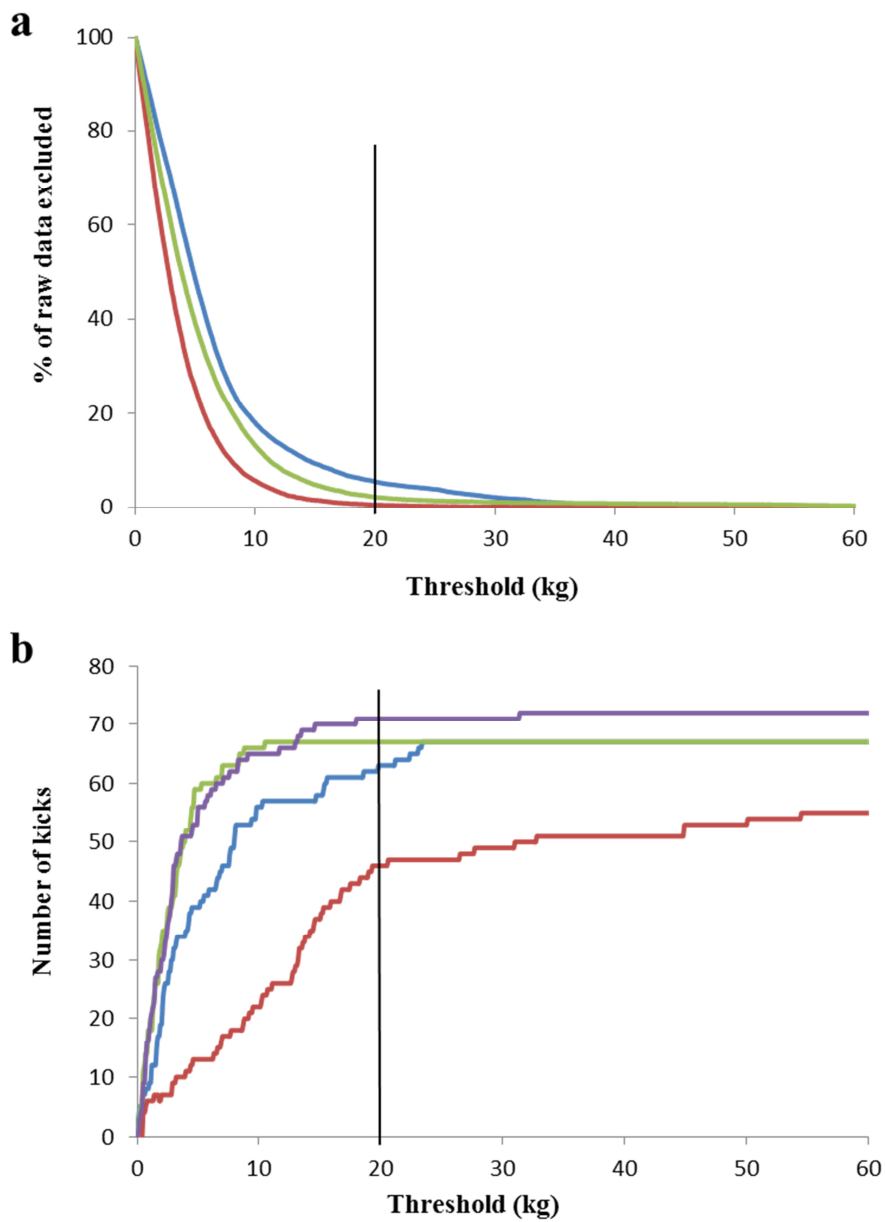


Fig. 3. Determination of the threshold for deleting erroneous data from the raw data and the effect of deleting erroneous data on the number of kicks that were analysed (every line represents measurements of an individual sow). Figure 'a' shows the percentage of raw data deleted when changing the threshold for removed erroneous data with an interval of 0.1kg. Figure 'b' shows the effect of removing erroneous data at different thresholds on the number of kicks. A threshold interval of 0.1kg was used. The final threshold for deleting erroneous data was set at 20 kg.

Table 1 – Definitions and measurement units of all force and visual stance variables.

	Variable	Definition	Calculated for these legs or combination of legs	Parameters [measurement units]
Force stance variables	Absolute weight	Weight exerted by one leg	LF, LH, RF, RH	mean, max, min, SD [kg], CV [%]
	Relative weight	$\left(\frac{\text{Absolute weight by one leg}}{\text{total weight of all four legs at that measurement time}}\right) 100$	LF, LH, RF, RH	mean, max, min, SD [kg], CV [%]
	Relative weight sum	Sum of relative weight of two legs	Left: LF + LH; Right: RF + RH; Hind: LH + RH; Front: LF + RF.	mean, max, min, SD [kg], CV [%]
	Kicks	Lifting of a leg in the air so that the absolute weight value falls below the threshold of 10 kg. The number and the duration of the kicks were considered.	LF, LH, RF, RH	-Number of kicks []; -Duration of kicks: mean, max, min, SD [s], CV [%]
	Weight shifts (WS)	A shift of absolute weight from one leg to another (lateral, anterior-posterior or diagonal). A weight shift was considered when the shift of absolute weight for each of both legs differed by more than 10 kg from the mean weight of the leg during the whole measurement period. The number, duration and magnitude of weight shifts were considered.	Left: LF-LH; Right: RF-RH; Hind: LH-RH; Front: LF-RF; Diagonal: LF-RH and RF-LH.	-Number of WS []; -Magnitude of WS: mean, max, min, SD [kg], CV [%]; -Duration of WS: mean, max, min, SD [s], CV [%]
	Leg Weight Symmetry (LWS)	Ratio of the absolute weight of two legs: $\left(\frac{\text{Absolute weight of lighter leg}}{\text{absolute weight of heavier leg}}\right) 100$	Left: LF-LH; Right: RF-RH; Hind: LH-RH; Front: LF-RF.	mean, max, min, SD [], CV [%]
Visual stance variables	Angle of the claw	The angle between the dorsal side of the claw and the floor	LH and RH	[°]
	Axis of pastern bone	The angle between the axis along the long pastern bone and the floor	LH and RH	[°]
	Angle of the hock	The angle of the tarsal joint formed between the stifle joint, the tibiotarsal joint and the metatarsophalangeal joint from a lateral view	LH and RH	[°]

L=left, R=right, F=front, H=hind

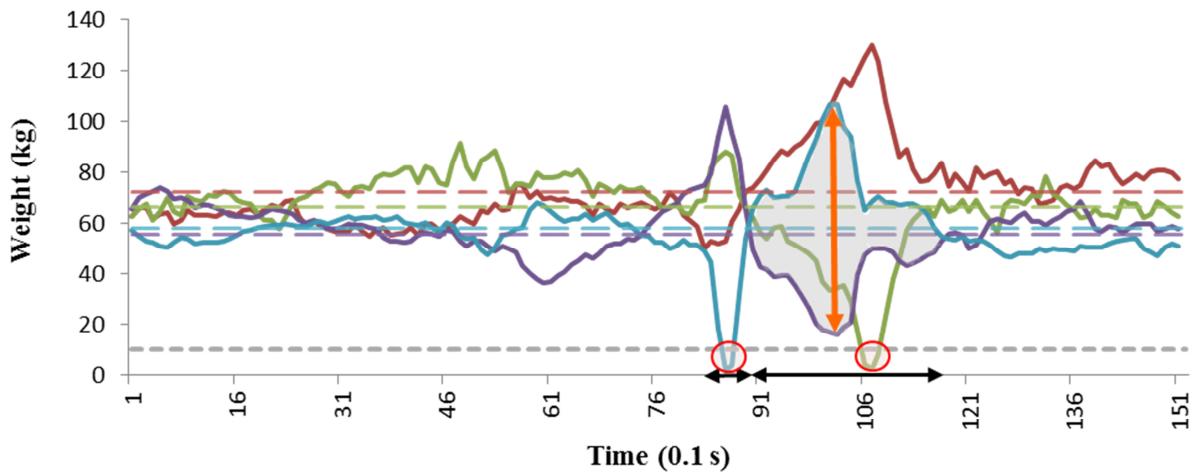


Fig. 4. Illustration of kick and weight shift in detail. Solid lines represent the absolute weight exerted by each of the four legs, dashed lines represent the mean of the absolute weights during the whole measurement (red = left front leg; green = right front leg; purple = left hind leg; blue = right hind leg). At approximately 8.5 s and 10.6 s this sow lifted its right hind leg and right front leg respectively. Both were analysed as a kick (visualised by red circles) because the absolute value of the weight went below the 10 kg threshold (indicated by dashed grey line). Also, at approximately 8.7 seconds, there is a weight shift between two legs. The grey zone illustrates the weight shift between the left hind leg and the right hind leg. The arrow in orange illustrates the maximum magnitude of this specific weight shift. The black arrows indicate the duration of the first kick and the duration of the weight shift.

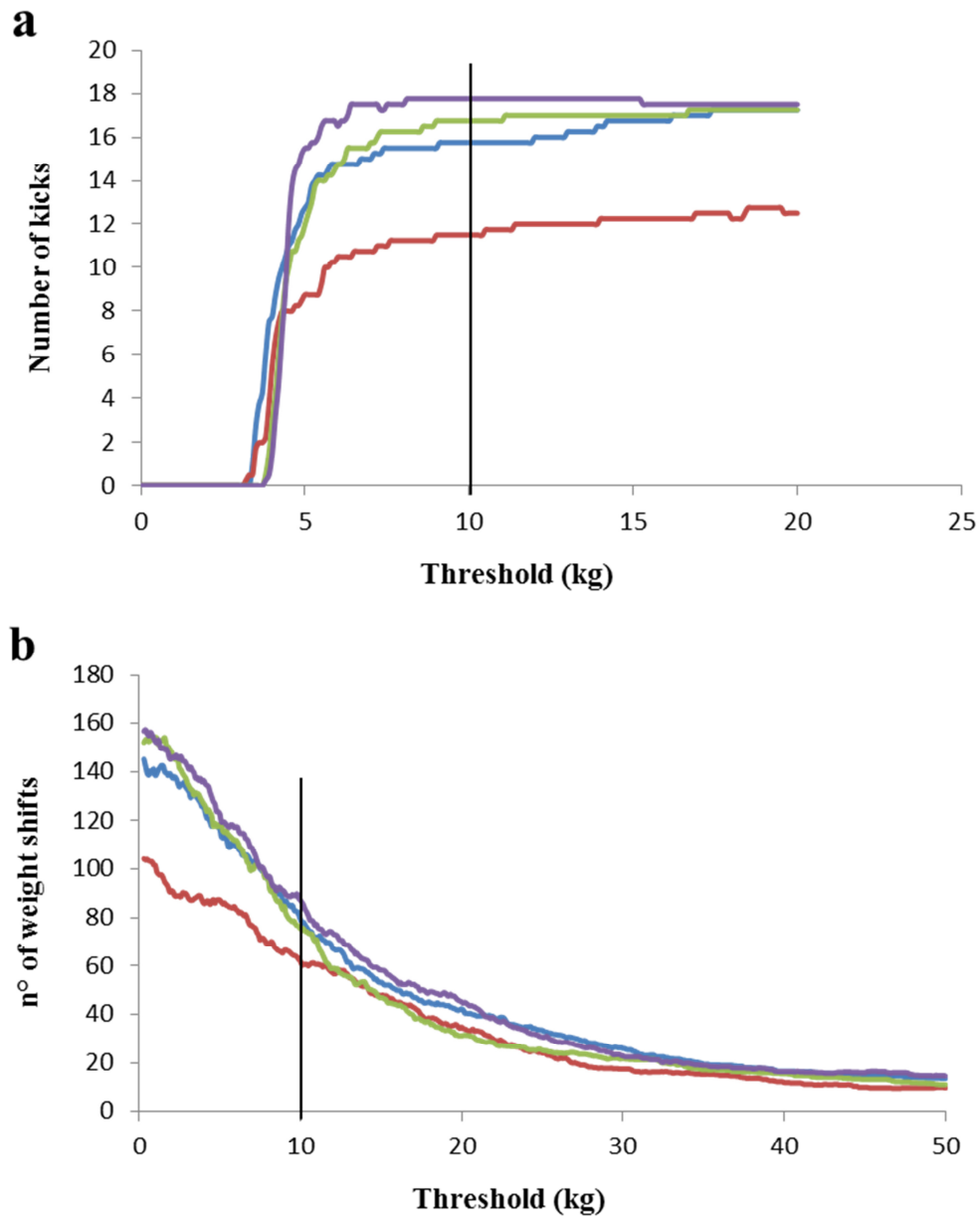


Fig. 5. Determination of the thresholds to detect kicks and weight shifts. Figure 'a' shows the number of kicks counted after removing erroneous data at a threshold of 20 kg and when changing the limit to detect kicks with an interval of 0.1 kg. A cut off value to detect kicks was set at 10 kg. Figure 'b' shows the number of weight shifts counted after removing erroneous data at a threshold of 20 kg and when changing the limit to detect steps for the calculation weight shifts with an interval of 0.1 kg.

3.3.4 REPEATABILITY OF VARIABLES

ANIMALS AND HOUSING

Twenty hybrid sows (Rattlerow Seghers) were selected at random from the ILVO's (Institute for Agricultural and Fisheries Research) research farm. All sows were at least four weeks pregnant, had a mean body mass of 248 kg (± 25 kg) and were housed in individual stalls on partially slatted, concrete floors. Sows were checked for lameness during walking using visual assessment (Welfare Quality®, 2009), performed by the first author. In the Welfare Quality® Protocol, a lame sow was defined as a sow unable to use one or more limbs in a normal manner varying in severity from reduced ability to bear weight, to total recumbency. One sow was found to be lame on the left hind leg. All other sows were found to be clinically sound.

MEASUREMENTS

The device was placed in front of the entrance of the gestation stable and sows were guided into the measurement box. After each single measurement the sows left the device, and entered the central corridor of the gestation stable through a loop to re-enter the measurement box for the next replication. During the measurements, sows were provided with straw and concentrate pellets. No sow was forced to enter the measurement box.

Five consecutive measurements of every sow were carried out within a time frame of one hour. A single measurement took ten minutes: five minutes to perform balance analysis and five minutes to take one picture of the hind legs and to reset the equipment for the next measurement.

STATISTICAL ANALYSIS

Data derived from the balances were automatically stored in the computer as text files, one file for each measurement.

To assess repeatability of the force stance variables and visual stance variables, the within-animal CV ($SD/mean \cdot 100\%$) was calculated. Values of within-animal standard deviation were first calculated over all five consecutive measures 'within sow'. A pooled within-animal standard deviation was calculated as the square root of the average of the squared standard deviation values for the 20 sows. This pooled within-animal standard deviation was divided

by the overall mean to obtain the within-animal CV (Quan and Shih, 1996). Given 20 animals with variable means M1.M20, the between-animal CV was calculated based on these means.

Repeated measures ANOVA was performed with consecutive measurements (categorical) as within subject variables using IBM SPSS Statistics 19 (IBM Corp., Armonk, New York, USA).

3.3.5 PROOF-OF-CONCEPT STUDY OF FORCE STANCE VARIABLES

STUDY DESIGN

A proof-of-concept study of the force stance variables measured by the system was performed at the ILVO research farm applying a case-control study design. During a three-month period, sows in the gestation stable were assessed daily for lameness. The locomotion scoring system was adapted from Main et al. (2000). A three-point numerical scale was used with score 0 (non-lame sow; fluent or stiff gait), score 1 (moderately lame sow; uneven weight distribution and stride length) and score 2 (severely lame sow; no weight bearing or lying down). Each time a sow was visually scored lame, this sow was tested with SowSIS and the data were added to the group of lame sows. For each lame sow a sound sow, matched by age and gestation stage, was randomly selected and tested with the system. The sound-sow data were added to the control group.

In a period of three months, four (severely) lame and four matched sound sows were measured ($n=4$ per group). Lame and sound sows, respectively, had a mean parity of 3.7 and 2.5, a mean body mass of 323 kg (± 21 kg) and 302 kg (± 30 kg) and were on average 92.5 (90 - 95) days pregnant. All lame sows were lame on the right hind leg.

STATISTICAL ANALYSIS

A paired *t*-test was used for comparison of means of the force stance variables between the matched-pair groups *i.e.* lame and sound sows. All analyses were performed using IBM SPSS Statistics 19 (IBM Corp., Armonk, New York, USA).

3.4 Results

3.4.1 DEVELOPMENT AND MEASUREMENTS

For both long measurements (evaluation of drift) and different positions on the top plate, the coefficients of variation were found to be very low. The coefficient of variation for long measurements (30 min) ranged from 0.26% to 0.29%. When reference masses were placed on different positions on the top plate, the CV ranged from 0.19% to 4.47%.

Figure 5 shows the output of the raw data of two different sows. Every line represents the actual weight exerted by one of the four legs. The sum of the weight of the four legs is drawn in orange. In Fig. 6a, the weight distribution of all four legs is almost equal and on visual assessment this sow was not lame. In Fig. 6b, however, the load exerted by the right hind leg is clearly lower compared to the load exerted on the other three legs. On visual assessment, this sow was scored lame on the right hind leg. The mean as well as the between-animal and within-animal CV of the force and visual stance variables are shown in Table 2. The mean total weight as sum of the four balances was $261.3 \text{ kg} \pm 27.6 \text{ kg}$. On average 58% of the total weight was carried by the front legs and 42% by the hind legs. Weight was almost equally divided between left and right side (49.7% and 50.3% respectively). The number of kicks was about twice as high on the hind legs (mean of 26 kicks) compared to the front legs (mean of 14 kicks) and the mean duration of a kick was longer as well on hind legs (0.34 sec on front legs, 0.49 sec on hind legs). The number of weight shifts was almost twice as high on the front legs as on the hind legs, whereas duration of weight shifts was similar for both front and hind legs. The number of weight shifts was the same for left versus right legs and when both crosswise related legs were compared. For all weight shifts, mean duration was equal. The magnitude of the weights shifts was comparable for left, right, front and hind legs but was higher compared to the magnitude of the weight shift for both crosswise associated legs. On each digital picture, three stance variables were calculated. For the 20 sows, a mean (SEM) angle of 51.7° (1.47), 47° (1.63) and 130.3° (1.08) was found for the angle of the claw, the axis of the long pastern bone and the angle of the hock, respectively.

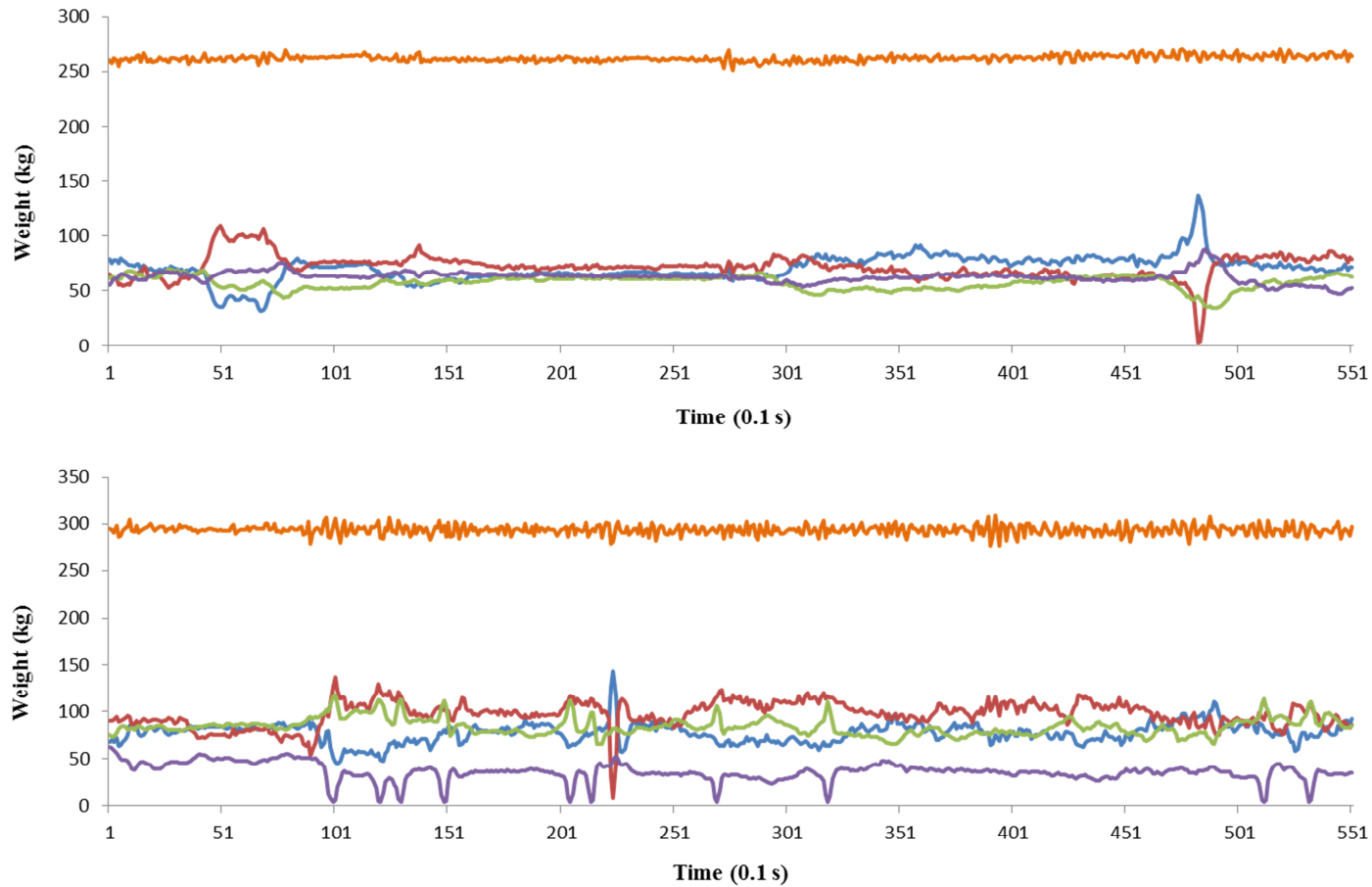


Fig. 6. Output of the balances. Every line represents the weight exerted by one leg during the measurement (blue = left front leg; red = right front leg; green = left hind leg; purple = right hind leg). The total weight as sum of the four balances is drawn in orange. Figure 'a' represents a non-lame sow where the average weight exerted by all four legs varies around the same value. Figure 'b' represents a lame sow that clearly places less weight on the right hind leg which was the affected leg.

Table 2 – Repeatability of all force and visual stance variables was studied. Twenty sows were each measured five times. The between-animal coefficient of variation (CV) of each variable over all sows and the within-animal CV over all five measurements are presented.

Variable		Unit	Mean	Within-animal CV (%)	Between-animal CV (%)
Mean absolute weight	absolute weight LF	kg	75.8	7.20	12.62
	absolute weight RF	kg	75.9	6.89	11.74
	absolute weight LH	kg	54.8	5.87	12.96
	absolute weight RH	kg	56.4	5.37	12.39
Mean relative weight	relative weight LF	%	28.9	7.33	6.75
	relative weight RF	%	28.9	7.02	5.20
	relative weight LH	%	20.8	5.08	8.02
	relative weight RH	%	21.4	4.57	6.77
	relative weight on Left side	%	49.7	4.08	2.93
	relative weight on Right side	%	50.3	4.03	2.90
	relative weight on Front legs	%	57.8	2.59	3.89
	relative weight on Hind legs	%	42.2	3.54	5.32
Kicks	N° kicks LF	-	7.6	66.30	51.43
	N° kicks RF	-	7.8	70.57	53.56
	N° kicks LH	-	13.2	42.16	57.29
	N° kicks RH	-	13.5	35.30	60.84
	duration kicks LF	s	0.38	69.41	49.32
	duration kicks RF	s	0.31	59.38	33.55
	duration kicks LH	s	0.48	119.11	83.31
	duration kicks RH	s	0.52	151.29	104.39
Weight shifts	N° WS LF-RF	-	99.1	23.63	23.68
	N° WS LF-LH	-	74.6	28.87	24.67
	N° WS LF-RH	-	43.8	34.89	23.46
	N° WS RF-LH	-	39.1	40.06	30.70
	N° WS RF-RH	-	71.2	28.41	26.91
	N° WS LH-RH	-	58.2	27.62	39.79
	Duration LF-RF	s	1.02	42.61	38.49
	Duration LF-LH	s	0.94	38.56	38.13
	Duration LF-RH	s	0.74	74.53	54.60
	Duration RF-LH	s	0.71	80.15	64.67
	Duration RF-RH	s	0.95	43.09	37.58
	Duration LH-RH	s	0.92	33.10	31.68
	Magnitude LF-RF	kg	50.7	14.36	8.94
	Magnitude LF-LH	kg	55.1	14.48	8.30
	Magnitude LF-RH	kg	37.6	17.79	8.02
	Magnitude RF-LH	kg	37.3	16.21	12.06
Magnitude RF-RH	kg	54.6	14.43	10.03	
Magnitude LH-RH	kg	62.5	11.63	14.92	
Leg weight symmetry	LWS Front legs	-	0.90	8.87	4.85
	LWS Hind legs	-	0.91	4.77	6.42
	LWS Left side	-	0.73	9.48	12.52
	LWS Right side	-	0.75	9.00	10.30
Visual stance variables	Angle of the claw	°	51.6	6.77	12.07
	Axis of pastern bone	°	47.0	13.03	14.70
	Angle of the hock	°	130.3	3.00	3.52

3.4.2 REPEATABILITY

The coefficients of variation for all force and visual stance variables are shown in Table 2. All force stance variables showed a low ($< 10\%$) to moderate ($\leq 15\%$) within-animal CV, except for number and duration of both kicks and weight shifts ($> 20\%$). Within-animal CV for all three visual stance variables were low with a CV of 7%, 13% and 3% for the claw angle, the axis of the long pastern bone and the angle of the hock, respectively. No significant differences were found between consecutive measures of force stance variables within a sow except for the number of weight shifts between left front and left hind leg ($P = 0.043$), duration of weight shift between left front and left hind leg ($P = 0.009$) and between right front and right hind leg ($P=0.004$) and for the magnitude between left front and left hind leg ($P = 0.007$). Concerning the three visual stance variables, no significant differences between the consecutive measures within a sow were found ($P > 0.05$; repeated measures ANOVA).

3.4.3 PROOF-OF-CONCEPT STUDY OF FORCE STANCE VARIABLES

The relevant and significantly different force stance variables between sound sows and sows that are lame at the right hind leg are summarized in Table 3.

No significant difference in absolute weight on both front legs was found between lame and sound sows. Mean absolute weight on the left hind leg was significantly higher whereas mean absolute weight on the right hind leg was significantly lower in lame sows. The maximum value for mean absolute weight exerted on the right hind leg was significantly lower when sows were lame on the right hind leg while their variation in putting weight on the left hind leg was higher compared to sound sows. Looking at the exerted weight related to the total body weight, lame sows showed a significantly higher maximum weight on the left hind leg and a significantly lower minimum weight on the right hind leg. Lame sows also put a higher percentage of their total weight on the left legs than sound sows (54% versus 49%; $P = 0.02$) and a lower percentage on their right legs (45% versus 50%; $P = 0.02$).

The number of kicks with the right hind leg was more than twice as high in the group of lame sows (mean 48) compared to the group of sound sows (mean 23). There was no difference in the number of kicks with the other three legs between both groups. The duration of kicks on the left hind leg tended to be about one third in lame sows than in sound sows ($P = 0.06$). The maximum duration of kicks was four times longer in sound sows.

Table 3 – Overview of the force stance variables that were different between non-lame and lame sows. Levels of significance: *, $P < 0.05$; **, $P < 0.01$; ., $P = 0.06$.

	Variables	Unit	Mean (SD)		Level of significance
			Non-lame	Lame (on RH)	
Absolute weight	absolute weight LH	kg	63 (8.6)	82 (3.4)	**
	absolute weight RH	kg	65 (4.1)	52 (8.3)	*
	max. absolute weight RH	kg	139 (10.3)	121 (7.2)	*
	CV absolute weight LH	%	30.1	21.6	*
Relative weight	min relative weight LH	%	1.28 (0.03)	1.14 (0.08)	*
	min relative weight RH	%	1.32 (0.09)	1.19 (0.1)	*
	max relative weight LH	%	47.16 (1.17)	49.22 (0.34)	*
	relative weight on Left side	%	49.82 (1.54)	54.09 (1.18)	*
	relative weight on Right side	%	50.18 (1.54)	45.91 (1.18)	*
Kicks	N° kicks RH	-	23 (5.2)	48 (12.3)	**
	duration kicks LH	s	0.40 (0.19)	0.15 (0.04)	.
	max duration kicks LH	s	1.23 (0.72)	0.25 (0.06)	.
Weight shifts	N° WS LF-LH	-	88 (10.8)	127 (16.2)	*
	duration WS LF-LH	s	0.90 (0.25)	0.67 (0.15)	*
Leg weight symmetry	LWS Hind legs	%	93.67 (8.99)	63.62 (9.88)	*
	LWS Right side	%	76.11 (10.51)	54.50 (8.02)	*

LF: left front leg; RF: right front leg; LH: left hind leg and RH: right hind leg.

Regarding weight shifts, lame sows showed a much higher number of weight shifts between the left front leg and left hind leg with a considerably shorter duration compared to the group of sound sows (0.90 s versus 0.67 s; $P = 0.03$).

Finally, the leg weight symmetry (LWS) between hind legs and the LWS between right legs were significantly different between lame and sound sows.

3.5 Discussion

3.5.1 DEVELOPMENT AND MEASUREMENTS

The developed system SowSIS has shown its practical use in an on-farm pilot study. Being demountable makes it possible to mount SowSIS almost anywhere in a stable without problems of carrying it through small corridors and around sharp turns. Sows easily adapt to the device as the construction is similar to a classical sow crate. The low CV when calibrated weights are placed on different places of the top plate indicates negligible impact of claw position on the results. The effect of drift during long measurements could also be ignored.

The uneven distribution of total weight between front and hind legs is consistent with results of previous studies (Thorup et al., 2007; von Wachenfelt et al., 2009b; Sun et al., 2011). The equal distribution between left and right legs found in this study refers to almost perfect symmetry between the left and right side of the body of a sound sow. Compared to the results of Sun et al. (2011), a slightly lower variation for side-to-side weight distribution was found. The doubled number of weight shifts on front legs compared to hind legs might have been influenced by foraging behaviour.

3.5.2 REPEATABILITY

The results of the repeatability study indicate that SowSIS allowed adequate registration of absolute and relative weight, magnitude of weight shift, leg weight symmetry and all visual stance variables with an acceptable repeatability. This was not the case regarding number and duration of kicks and number and duration of weight shifts. Pastell et al. (2006) found that the number of kicks and weight shifts was related to lameness but was influenced by restlessness and parity leading to the decision to divide cows in different groups. In this study, no distinction was made between quiescent and restless sows when analysing repeatability. Despite the moderate to high within-animal CV for kicks and weight shifts, these force stance variables were not yet excluded from future studies in sows. The high repeatability of the three visual stance variables demonstrates their potential use as an objective assessment of the posture of a sow. Only one other study (Bradley et al., 2009) calculated the angle of the claw, but they did not report the results. Consequently a comparison is not possible. To our knowledge, no other studies measuring the angle of the hock and the long pastern bone were conducted. Considering the importance of leg conformation for the longevity of sows (de

Sevilla et al., 2008; de Sevilla et al., 2009), visual stance variables for objective assessment of posture may be very helpful to and be used as possible additional criterion for the selection of young gilts. This will be the subject of future research.

3.5.3 PROOF-OF-CONCEPT STUDY OF FORCE STANCE VARIABLES

The absolute weight, the (minimum) relative weight, the number of kicks and both the number and duration of weight shifts show potential in the detection of unilateral lameness in sows. Absolute and relative weight clearly differ when a sow is lame on a specific leg. A sow significantly exerts less weight on the painful leg and more weight on the contralateral leg. Also, leg weight symmetry (LWS) between both hind legs and between the right legs was noticeably disturbed when sows were lame on the right hind leg. The significant difference in relative weight between left legs and between right legs also emphasized the imbalance between both hind legs. The number and duration of kicks can reveal lameness as well. This corroborated with results found in cows (Pastell et al., 2006). As the sow frequently lifts the affected leg the number of kicks increases. The shorter duration of the kicks on the contralateral sound leg arise as sows don't want to bear weight on their painful leg. Weight is shifted towards the sound side and towards the cross-related leg. The higher number of weight shifts between the lame leg and the contralateral leg can be explained by the sow trying to relieve the pain on the affected leg. Similar findings were observed in cows (Pastell et al., 2006). These preliminary results show potential of specific force stance variables in the detection of unilateral lame sows. Detection of lameness in case of bilateral disorders probably will be more complex compared to detection of unilateral lameness. However, bilateral lameness was not subject of research in this paper. Future work could be implemented in the following aspects: (1) the influence of restlessness on the output of kicks and weight shifts; (2) the measurement time and sample rate needed to have an efficient measurement; (3) large-scale validation in which randomly selected sows are assessed for lameness by visual examination and by SowSIS (visual and force stance variables) to determine the sensitivity and specificity of SowSIS; (4) the possibilities of visual stance variables to evaluate the relation between the posture of young gilts and their risk to become lame; (5) the ability of SowSIS to detect bilateral lameness and (6) the ability of SowSIS to detect incipient lameness at an earlier stage than visual assessment.

3.6 Conclusion

A transportable detection system, based on force stance variables derived from balance analysis and visual stance variables derived from image processing was developed: SowSIS (Sow Stance Information System). Five consecutive measurements (five replications) of twenty pregnant hybrid sows were carried out with SowSIS. The low to moderate mean within-animal coefficients of variation for all force and visual stance variables, with exception of kicks and weight shifts, revealed sufficient repeatability of the system. To evaluate the potential of detecting lame sows, an on-farm pilot study was performed with four sound sows and four lame sows (all of them lame due to right hind leg problems). Values of the force stance variables were compared between lame and sound sows. Absolute weight and relative weight exerted by a leg, leg weight symmetry and the number of kicks and weight shifts significantly differ between the lame and sound sows. Hence, SowSIS may be helpful to detect sows lame unilateral. A large-scale validation is necessary to reveal the usefulness of SowSIS as a detection tool of incipient lameness at an earlier stage than visual assessment. Both the developed system and the measured variables show potential to be used in future research on lameness in sows.

3.7 Commentary

The ultimate goal is to develop a practical system based on objective techniques that is able to detect incipient lameness in sows at an earlier stage than visual assessment and that can be used for lameness research purposes as well as for on-farm implementation. The research conducted in chapter 3 was the first step towards this goal.

Up till now a transportable, demountable device has been built, the proof-of-concept of the system has been demonstrated and the results have shown that SowSIS is able to discriminate unilateral lame from non-lame sows. Before the system can become fully operational, in lameness research settings or implemented on-farm as a management tool, much more research is required. This involves, inter alia, the development of a lameness detection algorithm and a large-scale validation study. Due to time constraints, these studies could not be carried out within the time frame of this dissertation. Further research necessary to obtain the ultimate goal - an objective, fully automated, early lameness detection system - has been described in subchapter 6.4.1.

As a consequence, lame sow detection in subchapter 3.3.5 and chapter 4 and 5 was still based on visual assessment. The visual locomotion scoring system used throughout this dissertation was adapted from Main et al. (2000). A three-point numerical scale was used with score 0 (non-lame sow; fluent or stiff gait), score 1 (moderately lame sow; uneven weight distribution and stride length) and score 2 (severely lame sow; hardly to no weight bearing or lying down). Because the number of severely lame sows was too low to be analysed separately, moderately and severely lame sows were merged into one category and only distinction was made between lame and non-lame sows when performing statistical analyses. The scoring system was tested for inter-and intra-observer agreement on an on-farm training day prior to data collection. Twenty sows were scored five times by two observers. The order in which sows were scored changed between the five repeated scorings. Agreement within and between observers was tested using the McNemar test and by calculating the kappa-coefficient between observers and between consecutive scorings within observer. A good to excellent agreement within observer was found ($\kappa > 0.65$). Due to the low agreement between observers ($\kappa < 0.4$) it was decided that lameness assessment would be carried out by one observer, i.e. the first author, in all studies described in this dissertation. The observer acquired skills in scoring lame sows during a seven-month period prior to data collection in which 421 sows were scored. The effect of training on the inter-observer reliability (IOR) could however not be studied as the IOR was not evaluated before training started.

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Prevalence of lameness and claw lesions throughout the reproductive cycle of sows and the impact on reproduction resultsⁱⁱ

4.1 Abstract

Lameness in sows is an emerging disease condition with major effects on animal welfare and economics. Yet the direct impact on reproduction results remains unclear. The present field study investigated the impact of lameness and claw lesions throughout the reproductive cycle on (re)production results of sows. In five herds, a total of 491 group-housed sows were followed up for a period of one reproductive cycle. Sows were assessed for lameness every time they were moved to another area in the herd. Claw lesions were scored at the beginning and at the end of the cycle. Reproduction results included the number of live born piglets, still born piglets, mummified fetuses and crushed piglets, weaning-to-oestrus interval and presence of sows not showing oestrus post-weaning, returning to service and aborting. Sows that left the group were recorded and the reason was noted. A mean prevalence of lameness of 5.9% was found although it depended on the time in the productive cycle. The highest percentage of lame sows (8.1%) was found when sows were moved from the post-weaning to the gestation stable. No significant associations were found between lameness and reproduction parameters with the exception of the effect on mummified fetuses. Wall cracks, white line lesions, heel lesions and skin lesions did have an effect on farrowing performance. Twenty-two percent of all sows left the group throughout the study and almost half of these sows were removed from the herd. Lameness was the second most important reason for culling. Sows culled due to lameness were significantly younger compared to sows culled for other reasons (parity: 2.6 ± 1.3 versus 4.0 ± 1.8). In conclusion, the present results indicate that lameness mainly affects herd productivity indirectly through its effect on sow longevity,

ⁱⁱ **Adapted from:** Pluym L. M., Van Nuffel A., Van Weyenberg S. and Maes D. (2013). Prevalence of lameness and claw lesions during different stages in the reproductive cycle of sows and the impact on reproduction results. *Animal* 7, 1174-1181.

whereas claw lesions directly affected some reproductive parameters. The high percentage of lame sows in the insemination stable indicate that risk factor studies should not only focus on the gestation stable, but also on housing conditions in the insemination stable.

4.2 Introduction

Lameness is a growing concern in swine breeding herds. Due to the pain, suffering and limited freedom of movement, lameness is recognized as an important welfare concern (Whay et al., 2003). Nowadays, the disease condition is implemented in the Welfare Quality® Assessment Protocol for pigs (Welfare Quality®, 2009).

Besides the impaired welfare, lameness is allied to financial loss estimated at 37 € per lame sow in Germany (Grandjot, 2007), 180 \$ per lame sow in the USA (Deen et al., 2008) and in a Dutch study, 20 to 30 € per sow present in the herd (Schuttert, 2008). Economic losses can be attributed to increased work load, higher veterinary costs due to treatment or euthanasia, higher risk for total or partial condemnation resulting in less slaughter revenue and to an impact on reproduction (Rowles, 2001; Schuttert, 2008). The impact on reproduction can be divided into a direct and an indirect effect. Literature on the indirect effect of lameness on reproduction is more widespread and much more consistent than the direct impact on reproduction.

Indirectly, lameness may affect reproduction of sows by influencing sows' longevity, behaviour and feed intake. Lameness is the most important reason for euthanasia and the second most important reason for involuntary culling (Engblom et al., 2007; Engblom et al., 2008; Jensen et al., 2010) leading to a detrimental impact on sow longevity. According to Bonde et al. (2004), lameness leads to uncontrolled lying-down behaviour and as a consequence, it may augment the risk of crushing piglets. The higher level of acute phase proteins in lame sows indicates the presence of inflammatory processes (Heinonen et al., 2006). Cytokines released by the inflammatory processes predispose to anorexia and lethargic behaviour (Johnson, 1997). In addition, Fitzgerald et al. (2012) reported a negative effect of overgrown toes on feed consumption during lactation. Early culling of sows, reduced feed intake and impaired locomotion indirectly decrease the mean number of litters per sow per year and the mean number of weaned pigs per sow per year, increasing the cost per weaned piglet.

The direct effect of lameness on reproduction (i.e. direct improvement or deterioration of the breeding or farrowing performance of a sow) however, is less clear. Several studies did not find any effect (Kroneman et al., 1993; Andersen and Bøe, 1999; Heinonen et al., 2006; Willgert, 2011) while other studies described a negative relationship between lameness and farrowing performance (Grandjot, 2007; Anil et al., 2009). Moreover, comparison between these studies is difficult as different methods and different stages in the reproductive cycle were used to assess lameness. As sows can recover over time, it may be recommended to assess lameness in the same sows at several times. In addition, knowledge on the stage in the reproductive cycle at which lameness is most prevalent, may have a key value regarding risk factor analysis.

In breeding herds, sows are commonly housed in three main areas: the insemination stable (shortly after weaning), the gestation stable and the farrowing crates. Each of these areas is related to a different physiological status of the sow and is characterized by its own specific floor, feeding strategy, environment and management. Several studies already referred to floor characteristics (Newton et al., 1980; Mouttotou et al., 1999) and feed (Simmins and Brooks, 1988) as important risk factors for claw lesions and lameness. When sows are moved to a new area within the herd, the possible risk factors for development of lameness to which sows may be exposed, will also change.

The aim of the present study was to evaluate the short term effect of lameness and claw lesions on (re)production at the three main stages of the reproductive cycle in sows. In addition, the prevalence of lameness and claw lesions was investigated at each of these three stages.

4.3 Materials and methods

4.3.1 ANIMALS AND HOUSING

A total of 491 sows from five randomly selected herds were included in the study. General information about every herd is given in Table 1. All herds had at least 750 sows and all sows were housed in group during gestation. In all herds, the gestation stable was provided with a partly slatted, concrete floor without bedding material. Herd one to four used free access stalls. In herd five, sows were housed in small groups of 15 sows per pen and were fed by use of trough feeding. Space per animal during gestation ranged between 2.0 and 2.6m². At the

insemination unit, sows were housed individually with solid concrete flooring in the front half and concrete slats in the rear half. Only in herd five metal slats were used in the rear half. The width of the concrete slats varied between eight and eleven centimetres whereas the metal slats measured one centimetre. Slots of the floors in all herds did not exceed two centimetres. Farrowing stalls contained cast iron, (partly) slatted flooring without bedding. During lactation, sows were provided feed and water ad libitum. As herd two had recently started with new sows, all sows had farrowed only once at the beginning of the study.

Table 1: Descriptive data of the herds (n=5) and the investigated group of sows in each herd in the study. Part of the sows left the group during the study due to culling, euthanasia, death, anoestrus, rebreeding or abortion. The mean parity of the sows that left the group as well as of the sows that remained in the group is also given.

	Herd 1	Herd 2	Herd 3	Herd 4	Herd 5
Herds in study					
Herd size (n° of sows)	1100	1000	1700	750	750
Breed	French Hybrid	PIC	Danbred	Danbred	Topigs-40
Batch farrowing system	Weekly	2-weekly	2-weekly	2-weekly	3-weekly
Type of group housing	FAS	FAS	FAS	FAS	Small pen
Litters/sow/year	2.2	2.5	NA	2.2	2.3
Piglets weaned/sow/year	23.6	29.2	NA	26.0	28.2
Piglets born alive/litter	11.6	12.8	NA	11.7	13.9
% stillborn piglets	10.8	4.4	NA	4.2	9.1
Sows in study					
Total n° of sows	54	109	141	86	101
Mean (SD) parity	2.3 (1.5)	1.0 (0.0)	3.3 (1.3)	2.1 (1.4)	3.8 (1.9)
Mean (SD) parity of sows that remained in the group	2.3 (1.7)	1.0 (0.0)	3.3 (1.4)	2.1 (1.5)	3.5 (1.7)
Mean (SD) parity of sows that left the group	2.3 (1.2)	1.0 (0.0)	3.1 (0.8)	2.2 (1.2)	4.4 (2.1)

FAS: Free access stalls

NA: data not available

4.3.2 MEASUREMENTS

Within each herd, one randomly selected group of sows was followed up for a period of one reproductive cycle (from weaning to weaning). Every group was investigated five times, i.e. two claw lesion scorings and three lameness assessments, over a period of five months (Figure 1). Visual lameness assessment was performed by the first author the day sows were moved from one stage in the herd to another (L1, L2, and L3). A three-point numerical scale adapted from Main et al. (2000), was used with score 0 (non-lame sow; fluent or stiff gait), score 1 (moderately lame sow; uneven weight distribution and stride length) and score 2 (severely lame sow; no weight bearing or lying down). Due to the small number of severely lame sows in the present study score 1 and 2 were merged into one category and only distinction was made between lame and non-lame sows in further analysis. Claw lesion scoring was carried out twice in the farrowing stable: one week before sows were weaned (C1) and one week after farrowing (C2) (Fig. 1).

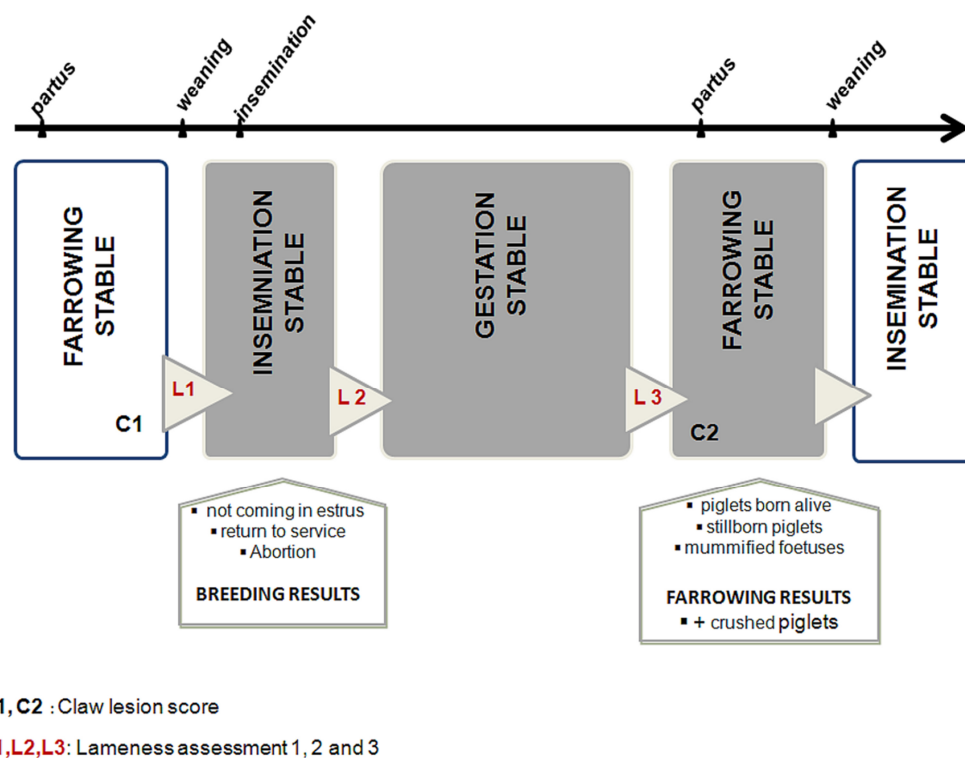


Fig. 1. Measurements during the reproductive cycle of the sows: Lameness assessment was performed when sows were moved between different stables (L1 to L3). Claw lesion scoring was performed in the farrowing stable: one week before weaning and one week after farrowing (C1 and C2). Reproduction data of one period were considered (breeding performance, farrowing performance and crushed piglets).

Seven claw parameters were scored: length of toes, length of dew claws, wall cracks, heel cracks and/or overgrowth, skin lesions above the claw, heel-sole cracks and white line cracks. The first five parameters were based on the Dutch scoring method “Nederlandse Zeugenklauwencheck” (Hoofs, 2006). The last two parameters were scored following the Zinpro®FeetFirst method (Feet First® Team, 2010). Each of the four claws of the hind legs were scored from one to four, with score one meaning no lesion and score four meaning a severe lesion. The sum of the score of the four claws was made and was called the ‘total score’ (min 4 – max 16). However, when performing statistical analysis, total score was included as a dichotomous variable. This means that sows without lesions on any of the four claws (= total score 4) were coded zero and sows with a total score of 5-16 were coded one. By summing the seven ‘total scores’, a ‘global score’ was obtained for each sow (min 28 – max 112). For the data and statistical analyses, global scores were regarded as continuous variables.

Parity of sows was categorized into four groups: 1, 2, 3 to 5 and ≥ 6 parity. Reproduction results in this study are defined as a combination of the farrowing performance, crushed piglets and the breeding performance. Information on farrowing performance and crushed piglets that was collected for the investigated cycle, included the number of piglets born alive (continuous variable) and absence or presence of stillborn piglets, mummified foetuses and crushed piglets (dichotomous variables). The breeding performance of sows included ‘showing oestrus post-weaning’, ‘weaning-to-oestrus interval’, ‘returning to service’ and ‘abortion’ (defined as expulsion of foetuses between day 35 and day 108 of gestation). The weaning-to-oestrus interval was regarded as a continuous variable, the other three as dichotomous variables. Coming into oestrus within 10 days after weaning, positive pregnancy diagnosis by ultrasound scanning 23 - 35 days after breeding and absence of abortion were coded as normal (zero).

Sows that left the group during the study were recorded as well as the time and the reason (not coming in oestrus, returning to service, abortion, death, euthanasia or culling). As it is essentially different, distinction was made between sows that left the group because they were removed from the herd (‘sows removed from the herd’) and sows that left the group but that remained in the herd (‘sows removed from the group’). The reasons for removing sows from the herd was culling, euthanasia or death. The reason why sows left the group but remained in the herd was because they did not show oestrus, they returned to service or they aborted.

An overview of the reproduction results across all herds is given in Table 2.

Table 2: Overview of the farrowing and breeding performance of the sows in the study. Descriptive data on the number of piglets born alive, stillborn piglets, mummified foetuses and crushed piglets over all 381 sows as well as descriptive data on breeding performance including the mean weaning-to-oestrus interval and the mean number and percentage of sows that did not show oestrus, did return to service or aborted during the study.

		Mean	SEM	Minimum	Maximum
Farrowing performance	Piglets born alive	14	0.18	0	23
	Stillborn piglets	1.2	0.08	0	11
	Mummified foetuses	0.5	0.05	0	7
Crushed piglets		0.6	0.06	0	11
		Mean	SEM	Mean percentage	
Breeding performance	Weaning-to-oestrus interval	6.0	0.33	–	
	Number of sows:				
	not showing oestrus	24	–	6	
	Returning to service	39	–	10	
	Abortion	4	–	1	

4.3.3 STATISTICAL ANALYSIS

Normality of continuous variables was evaluated. Linear and logistic regression models were built with farrowing and breeding related variables as dependent variables. To account for the clustering of sow in the herd, a fixed herd effect was included. In addition, total and global claw lesion scores as well as lameness and parity were included as fixed effects. A stepwise forward model building procedure was followed and all factors with a P-value < 0.05 were retained in the final multivariable model.

Descriptive statistics were used to illustrate the prevalence of claw lesions and lameness throughout the productive cycle. To evaluate if parity and global score differ between healthy and lame sows (0/1), between sows that were (1) or were not (0) removed from the herd, and

between sows removed due to lameness (1) or due to other reasons (0), univariable linear regressions, with either parity or global score as dependent variable and herd as fixed effect, were performed. To evaluate the difference in global score between the first and the second claw lesion scoring, mixed model linear regression was performed with global score as dependent variable, sow as random effect, to correct for repeated measurements, and time of claw lesion scoring, herd and interaction time*herd as fixed effects.

All statistical analyses were performed using IBM SPSS Statistics 19 (IBM Corp., New York, USA).

To analyse the effect of the three measuring periods (L1, L2 and L3) on lameness, a multilevel logistic regression model was fit using MLwiN 2.02 (Centre for Multilevel Modelling, Bristol, UK). Herd (1 to 5), measuring period and the interaction herd*measuring period were included as fixed effects.

4.4 Results

4.4.1 IMPACT ON (RE)PRODUCTION RESULTS

After stepwise forward model building, significant associations were found between the independent variables (parity, lameness, claw score and herd) and the dependent variables (stillborn piglets, mummified foetuses, crushed piglets and number of live born piglets) (Table 3). In the final model, no significant associations between risk factors and breeding performance (showing oestrus post-weaning, weaning-to-oestrus interval, returning to service and abortion) were found. However, several claw lesions were related to farrowing performance. Presence of skin lesions above the claw ($P = 0.021$) and white line lesions ($P = 0.036$) significantly increased the odds of stillborn piglets. Heel lesions were significantly associated with presence of crushed piglets ($P = 0.017$). The odds of mummified foetuses decreased when wall cracks were present ($P = 0.044$). An influence of lameness could only be found for the presence of mummified foetuses. The odds of having mummified foetuses was twice as high in lame sows compared to healthy sows. A significant herd effect was found for all of the farrowing results while parity was significantly associated with the presence of stillborn piglets and crushed piglets (Table 3).

Table 3: Final multivariable logistic regression models related to the risk factors for farrowing performance and crushed piglets with herd, parity, claw score and lameness as independent variables and presence of stillborn piglets, mummified fetuses and crushed piglets as dependent variables. Regression analyses were based on the results of 306 sows.

	Variable	<i>n</i>	<i>b</i>	SEM	Odds ratio	95% CI	P-value
Stillborn Piglets (0/1) ^e	Intercept		0.24	0.47	...		
	Herd	5					0.025
	Parity	4					0.012
	Parity 1		ref.	...			
	Parity 2		1.61	0.51	5.00	[13.59-1.84]	0.002
	Parity 3-5		1.14	0.43	3.14	[7.26-1.35]	0.008
	Parity ≥ 6		1.27	0.73	3.56	[14.89-0.85]	0.080
	White line 1 ^a	306	0.65	0.31	1.91	[1.04-3.51]	0.036
Skin 1 ^b	306	1.42	0.62	4.13	[1.23-13.79]	0.021	
Mummified Foetuses (0/1) ^e	Intercept		-1.08	0.43	...		
	Herd	5					0.052
	Wall cracks 1 ^c	306	-0.75	0.37	0.47	[0.23-0.98]	0.044
	Lameness	306	0.87	0.35	2.38	[1.19-4.75]	0.014
Crushed piglets (0/1) ^e	Intercept		1.58	0.97	...		
	Herd	4					<0.001
	Parity	4					0.029
	Parity 1		ref.	...			
	Parity 2		0.20	0.52	1.23	[3.38-0.44]	0.696
	Parity 3-5		1.18	0.47	3.24	[8.17-1.29]	0.013
	Parity ≥ 6		1.29	0.73	3.63	[15.19-0.87]	0.077
	Heel lesions1 ^d	236	-2.23	0.93	0.11	[0.02-0.67]	0.017

^aTotal claw score for white line lesions, ^bTotal claw score for skin lesions above the claw, ^cTotal claw score for wall cracks, ^dTotal claw score for heel cracks and overgrowth. The number behind the total score refers to the first time (at weaning) or second time (at farrowing) claw lesion scoring was performed. ^eAbsence (0) or presence (1) of stillborn, mummified and crushed piglets, respectively. *b*: regression coefficient, Ref.: reference

4.4.2 PREVALENCE OF CLAW LESIONS

The percentage of sows with and without lesions for each of the seven claw parameters that were scored the first and second time claw lesion scoring was performed, are represented in Figure 2. Heel cracks were found to be the most frequent lesions (96% sows with lesions) whereas skin lesions above the claw were only occasionally found (8% of sows with lesions). No significant difference in global score, the sum of seven total scores, was present between the sows that remained in the group and the sows that left the group during the study. In general, the mean global score slightly improved from first (mean(SD) score of 35.8 (3.9)) to second time (mean(SD) score of 34.9 (3.2)). However, a significant herd*time interaction ($P = 0.012$) was found. The change between the first and second global score was found to be significant only at herd one and four.

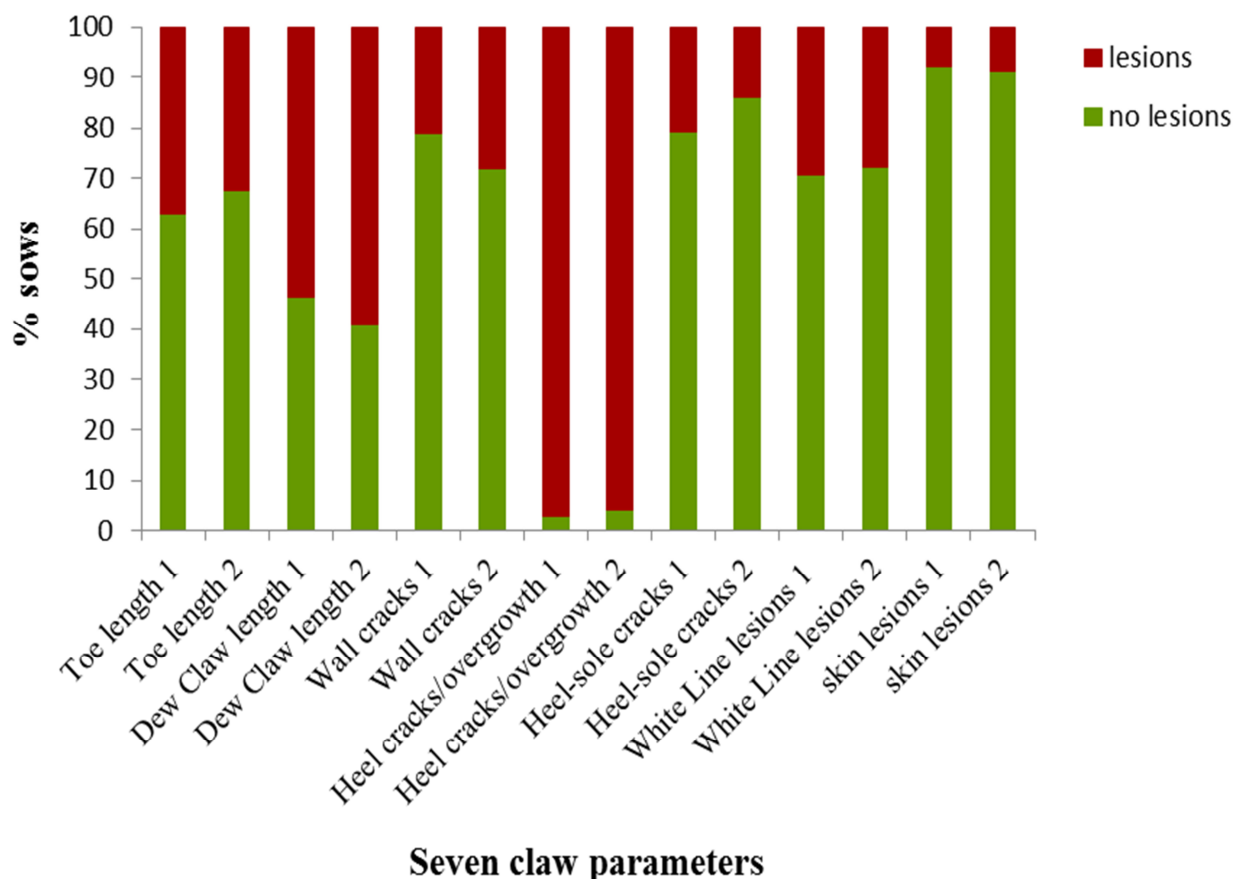


Fig. 2. Percentage of sows (total of 381) with and without lesions for each of the seven claw parameters that were scored at the first (1) and second (2) time claw lesion scoring was performed.

4.4.3 PREVALENCE OF LAMENESS

In total, 106 sows (21.6%) left the group during the study. Of these, 54 sows (51.0%) were removed from the group with returning to service as most important reason. The remaining 52 sows (49.0%) were removed from the herd due to culling, euthanasia or death. Possible reasons for removal from the herd included: 'udder health', 'leg and feet problems', 'death', 'disease', 'anoestrus', 'rebreeding', 'problems during farrowing', 'low production', 'poor maternal characteristics' and 'removed for unknown reason'. Udder health problems (33%) and feet and leg problems (15%) were the most important reason for culling. Sows that were removed from the herd had a mean parity of 4.0 ± 1.8 whereas sows specifically culled due to feet and leg problems had a mean parity of 2.6 ± 1.3 .

Figure 3 shows the percentage of sows that were scored lame at the three visual lameness assessments (L1-L2-L3). The mean percentage of lame sows for all herds was $5.5\% \pm 3.3$, $8.1\% \pm 6.1$ and $4.1\% \pm 4.4$ at L1, L2 and L3, respectively. The odds of a sow to be lame significantly differed between L1, L2 and L3 ($P = 0.027$) and significantly varied according to the herd ($P = 0.002$). The interaction between herd and measuring period was not significant. In every herd, the percentage of lame sows peaked at the moment of the second lameness investigation i.e. when sows were moved from the insemination stable to the gestation stable. At L1, 27 sows were assessed to be lame. Of these, nine sows left the group before L2 could be performed. At L2, a total of 32 lame sows was found. Only two sows that were lame at L1 were still lame at L2 and four sows that were lame at L2 were also lame at L3. There was no significant difference in parity between sows that were lame (mean parity of 2.6 ± 1.7) and sows that were not lame (mean parity of 2.5 ± 1.7).

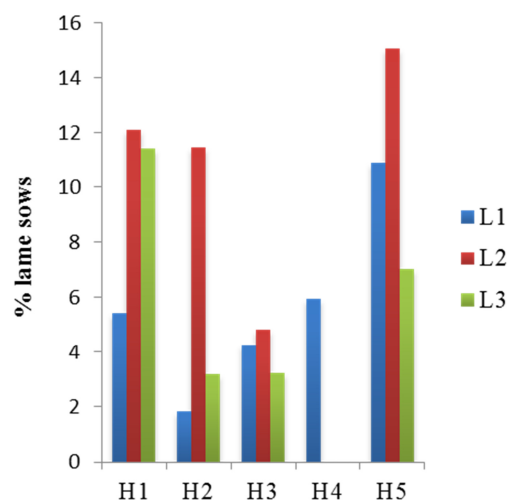


Fig. 3. Percentage of sows that were lame at the three visual lameness assessments (L1 to L3) for each herd (H1 to H5).

4.5 Discussion

4.5.1 DIRECT IMPACT

Based on the models, some claw lesions seem to have a direct impact on farrowing performance of sows. An effect of claw lesions on reproductive performance was also reported by De Pita (2010), Anil (2011) and Fitzgerald et al. (2012) but could not be shown by Enokida et al. (2011). In the present study, white line lesions and skin lesions above the claw increased the risk for stillborn piglets. Both skin lesions and white line lesions may facilitate entry of bacteria causing infection, pain and clinical lameness. An association between white line lesions and lameness in breeding sows was described by Anil et al. (2007). De Pita (2010) reported a positive association between white line lesions and the likelihood of having ≤ 10 piglets born alive. In the same study, the likelihood of having ≤ 10 piglets born alive, was positively associated with the number of stillborn piglets. The reason why sows with wall cracks have a lower odds of having mummified foetuses remains unknown.

Contrary to claw lesions, a clear direct impact of lameness on breeding and farrowing performance could not be shown with the exception of the effect on mummified foetuses. Lameness is a clinical sign that movement is painful. The higher serum concentrations of acute phase proteins in lame sows reported by Heinonen et al. (2006) indicate the presence of

inflammatory processes. Pain and inflammation may cause reduction of feed intake and consequently may lead to a poor body condition of the sow. In three herds, body condition of sows was scored by means of backfat measurements. In this preliminary study presence of lameness was related to a lower backfat thickness (unpublished data). Poor body condition has been associated with the presence of mummified foetuses in sows (Knauer et al., 2006).

Apart from the effect on mummified foetuses, no effect of lameness on reproduction was found in the present study. This is in contrast with the lower number of piglets born alive and higher piglet losses before weaning reported by Grandjot (2007) and Anil et al. (2009). The absence of a significant association between lameness and reproductive performance may be explained by the fact that reproduction results may strongly differ between individual sows. Therefore, it can be suggested to evaluate the impact on reproduction in longitudinal studies covering several reproductive cycles and using a sow as her own reference. However, in this study parity and herd, as indicator for breed effect, were already taken into account when performing linear and logistic regression.

4.5.2 INDIRECT IMPACT

Besides the direct impact, lameness and claw lesions are assumed to have an indirect impact on reproduction results. Indeed, a relationship with the risk of removal from the herd was found as well as a significant association between heel lesions and crushed piglets.

With a percentage of 15%, feet- and leg problems appeared to be the second most important reason for sow removal in this study. Moreover sows removed from the herd because of feet and leg problems were significantly younger compared to sows removed due to other reasons. The finding that feet and leg problems are important reasons of early culling, is in agreement with the results of other studies (Engblom et al., 2007; Jensen et al., 2010). Sows reach peak production between the third and sixth parity. Hence, removal of sows at a mean parity of 2.6 implies that part of the sows did not reach their most productive parities, nor repaid their investment costs yet (Ritter et al., 1999; Stalder et al., 2003; Anil et al., 2009). A higher removal rate also increases replacement costs and the frequency of adding new gilts which in turn implicates a higher health risk to the animals currently in the herd.

In this study, a negative association was found between presence of heel lesions and presence of crushed piglets. Heel lesions are very common among sows. The high percentage of sows

with heel lesions (96%) in this study is in agreement with the results of previous studies (Gjein and Larssen, 1995; Anil et al., 2007; Pluym et al., 2011). Only a few sows did not have any heel lesion. Due to the low number of sows without lesions, the association found between heel lesions and crushed piglets may not be an effect but just coincidence.

4.5.3 PREVALENCE OF CLAW LESIONS AND LAMENESS

To be able to perform thorough risk factor analysis and to start prevention at the right moment, knowledge on the changes in prevalence of lameness and claw lesions throughout the reproductive cycle is important. The mean global score in general remained unchanged but significantly improved from first to second claw lesion scoring in herd one and four. Trimming of long toes and healing of lesions may have contributed to this improvement. The high prevalence of sows with heel cracks and overgrowth was also observed in other studies (Gjein and Larssen, 1995; Anil et al., 2007; Pluym et al., 2011). The mean prevalence of lameness namely 5.6%, 8.7% and 5.1% at L1, L2 and L3, respectively, were slightly lower compared to the prevalence of 9.7% that was found in an earlier study performed on Belgian herds (Pluym et al., 2011). Large differences between herds, as seen in other studies (Heinonen et al., 2006; Pluym et al., 2011), were also noticed in this study. Group housing is mentioned as an important risk factor for lameness (Anil et al., 2005; Chapinal et al., 2010). Notwithstanding, in this study the prevalence of lameness was lowest at the end of the gestation period (L3) and highest at the moment sows were moved from the insemination stable to the gestation stable (L2). In herd two, lameness assessment could not be done when sows were moved from the insemination to the gestation stable and therefore had to be done two weeks after the sows were introduced in group housing (stable groups). However, even without this herd, the prevalence remained highest at L2 (data not shown). Group housing probably can influence development of lameness. Especially shortly after introduction when sows fight to establish a dominance hierarchy. When this equilibrium is found, sows may have the time to heal from their injuries (Arey, 1999). Nevertheless, results of this study suggest that also housing in the insemination stable may have an impact on the development of lameness. The increase in prevalence at L2 is caused by a higher number of lame sows and not by a lower number of total sows due to sows leaving the group between L1 and L2. In the insemination stable, sows were housed in conventional stalls. Due to immobility, muscle conformation and bone strength can deteriorate (Marchant and Broom, 1994). However, in the

present study, sows were housed in stalls for at most five weeks whereas impact of restricted mobility on the development of muscle and bone strength (Marchant and Broom, 1994) as well as on lameness (Karlen et al., 2007) could only be shown after housing sows in stalls during almost the entire gestation period.

Besides the differences between L1, L2 and L3, the prevalence of lameness significantly varied between herds. Differences in management (e.g. handling of animals, moving the sows at the time of oestrus detection) might explain the variation between herds. These results indicate that the prevalence of lameness differs throughout the reproductive cycle and that changes vary according to the herd. This substantiates our suggestion that lameness should be assessed several times during the reproductive cycle.

4.6 Conclusion

A direct effect of certain claw lesions on the farrowing performance of sows was shown, whereas for lameness, a clear indirect impact on (re)production results was found. The prevalence of lameness differed between herds and varied throughout the reproductive cycle. Housing in the insemination stable seems to induce more lameness than housing in the gestation stable in the herds studied. Therefore, further investigation on risk factors especially related to the insemination stable and introduction of sows in group housing is needed.

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Risk factors for sow lameness development within the first days of group-housingⁱⁱⁱ

5.1 Abstract

Lameness in sows is an important welfare issue that is affected by housing conditions and is thought to be influenced by the hierarchical fights within the first days after moving them to the group housing. A longitudinal study on 15 randomly selected herds was performed to investigate the incidence of sow lameness and possible risk factors within the first days of group-housing. Each herd was visited just before and again three to five days after sows were moved to the gestation unit (*i.e.* group-housing). Dimensions and quality of the housing environment of group-housing were assessed. Of each sow, locomotion, body condition, skin lesions and dirtiness were scored. Information on housing and management was obtained using a questionnaire. In total, 810 sows were included. The median incidence of lameness in each herd was 13.1% (0 – 27.3). Sows with more than 10% of the body covered with manure showed an increased risk for lameness development (OR = 2.33, $P = 0.001$). An increase of space allowance from 1.67 m² to 3 m² (OR = 0.40, $P = 0.03$) and of herd size from 144 to 750 sows per herd (OR = 0.71, $P = 0.02$) decreased the risk for lameness development. The degree of aggression, indicated by skin lesions, nor the floor characteristics influenced lameness development. These results indicate that sows may benefit from a higher floor area. More research is necessary to define the optimal space allowance to prevent sow lameness, and to investigate factors influencing the association between sow dirtiness, herd size and lameness development.

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5.2 Introduction

Since 2013, group-housing of gestating sows from 28 days after service until 1 week before farrowing is mandatory in all member states of the European Union (European Commission, 2008). Although the change in sow housing was primarily driven by welfare concerns (Appleby, 2005), group-housing may also present welfare issues including injuries caused by post-mixing aggression and a higher prevalence of lameness (Gjein and Larssen, 1995a; Backus et al., 1997; Anil et al., 2003; Estienne et al., 2006; Chapinal et al., 2010). Lameness has been reported to occur in 8% to 15% of group-housed sows (Gjein and Larssen, 1995b; Bonde et al., 2004; Heinonen et al., 2006; KilBride et al., 2009; Pluym et al., 2011) although the number of lame sows can change throughout the reproductive cycle (Pluym et al., 2013) and even during the period of group-housing (Kroneman et al., 1993; Gjein and Larssen, 1995b; Díaz et al., 2013). Most of the lameness cases during group-housing has been reported to develop shortly after introduction into the group (Kroneman et al., 1993; Anil et al., 2005; Chapinal et al., 2010). Kroneman et al. (1993) reported a lameness incidence of 10% within the first month. However, more recent data on the incidence at that moment are lacking.

Identifying influential factors is essential to prevent lameness development. Lameness may develop for several reasons including inadequate management and housing conditions. Floor space per sow, group size and flooring condition are main components that may be involved. The impact of space allowance on lameness development in group-housed sows has already been studied but results are inconsistent. Gjein and Larssen (1995b) and Heinonen et al. (2006) did not find an association whereas Salak-Johnson et al. (2007) reported a higher risk for lameness with increased space allowance. The effect of space allowance on lameness development may be dependent on group size, as was demonstrated for finishing pigs (Street and Gonyou, 2008). For group-housed sows however, studies investigating the association between group size and lameness are lacking. Bare, slatted concrete floors, predominantly used for group-housing of gestating sows, have clearly been associated with lameness (Andersen and Bøe, 1999; Heinonen et al., 2006; KilBride et al., 2009). Slipperiness, abrasiveness, hardness, surface profile, void ratio and cleanliness are the main characteristics contributing to a floor's injury potential (Kovacs and Beer, 1979; Webb and Nilsson, 1983; Webb, 1984; McKee and Dumelow, 1995). However, these characteristics have not yet been subject of risk factor analysis targeted for lameness and standards regarding floor characteristics other than slipperiness (Penny et al., 1965; Thorup et al., 2007) are lacking for group-housed sows.

As soon as pigs are grouped together, fighting occurs in order to establish hierarchy. In sows, social ranking is established after two to three days (Arey and Edwards, 1998). Within the first hours post-mixing, aggression may be intense and result in skin lesions and injuries (Turner et al., 2006). Aggressive encounters among sows have been suggested to result in lameness (Kroneman et al., 1993; Gjein and Larssen, 1995b; Chapinal et al., 2010) but the association has not yet been scientifically proven.

The aim of the present study was to determine risk factors for lameness development within the first days of group-housing, with a focus on housing conditions, management and post-mixing aggression.

5.3 Materials and Methods

5.3.1 STUDY DESIGN AND STUDY POPULATION

The study was conducted in compliance with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) statement guidelines (von Elm et al., 2007).

Data were collected from 15 randomly selected herds (Table 1). Herds were selected using the pig herd national database of the Belgian Federal Agency for Food Safety. The following eligibility criteria were applied: sow herd or farrow-to-finish herd, group-housing of sows during gestation, use of a sow batch production system and willingness of the farmer to participate in the study. Herds using bedding material, e.g. straw for the gestating sows were excluded. Herd size ranged from 144 to 750 sows (median = 400). On each herd, one batch of sows was randomly selected. The sample size to detect lameness was at least 32 sows per herd and was calculated based on Dohoo et al. (2009).

$$n = (1 - (\alpha)^{1/D}) \times \left(N - \frac{D - 1}{2} \right)$$

Where n = required sample size, α = 1 – confidence level (here 0.05), D = estimated minimum number of diseased animals in the group (here 8%), N = population (herd) size. All sows within one batch were included in the study. Due to fewer than 32 sows within one batch on some herds, the minimum number of sows was not met on three herds.

Table 1: Herd size, number of sows investigated, sow breed and feeding system during gestation for each of the 15 herds in the study.

Herd ID ^a	Herd size	Investigated sows	Sow breed	Feeding system
1	350	38	Finnish Landrace	Free access stalls
2	560	98	Dalland	Free access stalls
3	210	32	Topigs 20	Free access stalls
4	450	55	Topigs 20	Trough feeding, no barriers
5	180	24	Topigs 20	Free access stalls
6	210	38	Danbred	Free access stalls
7	144	32	JSR	Electronic sow feeders
8	750	63	Danbred	Free access stalls
9	550	61	PIC ^b	Trough feeding, partial barriers
10	240	24	crossbreds	Free access stalls
11	225	9	Belgian Landrace	<i>ad libitum</i> feeding
12	400	90	JSR	Electronic sow feeders
13	745	99	Dalland	Trough feeding, no barriers
14	450	73	Topigs 20	Free access stalls
15	500	91	PIC ^b	Vario-Mix

^a Herd identification number; ^b Pig Improvement Company

5.3.2 DATA COLLECTION

Between 21 and 28 days postpartum sows were weaned and moved to the insemination unit where they were kept in individual stalls. Four weeks after artificial insemination, they were moved to the gestation unit where they were kept in group-housing. Each herd was visited twice. First on the day sows were moved from the insemination to the gestation unit and again three to five days after the sows were introduced in the group.

Data collection comprised the assessment of dimensions and quality of the housing environment of the gestation unit as well as locomotion, body condition, skin lesions and dirtiness scoring of sows. In addition, the farmer was asked to fill in a questionnaire concerning general herd characteristics as well as housing conditions, management and feeding and water provision practices of the insemination and gestation unit (see Appendix). To control for information bias, answers were run through by the first author through face-to-

face interviews of the pig farmers and inspection of the stables. Information on the parity and breed of the animals were obtained from the sow herd management database.

LAMENESS DEVELOPMENT

Locomotion was assessed by the first author during the first and second herd visit to detect lameness development resulting from the post-grouping period. Sows were made to walk until a clear view of the locomotion could be obtained. The locomotion scoring system was adapted from Main et al. (2000). A three-point numerical scale was used with score 0 (non-lame sow; fluent or stiff gait), score 1 (moderately lame sow; uneven weight distribution and stride length) and score 2 (severely lame sow; no weight bearing or lying down). The locomotion score for both herd visits was transformed into a binary ‘lameness development score’ by taking the non-lame sows into account from the first visit and further classifying these sows as ‘not lame’ (in case of score 0 on the second visit, or ‘became lame’ in case of score 1 or 2 on the second visit.

FLOORING

The group-housing system for the pregnant sows in each herd was recorded and the mean floor area available to each sow was calculated. During the second herd visit, dirtiness, quality, wetness and slipperiness of the floor were assessed at the gestation unit. The protocol to measure and score the floor characteristics is described in Table 2.

BODY CONDITION, SKIN LESIONS AND SOW DIRTINESS

The protocol to assess the body condition, skin lesions and dirtiness of each sow is described in Table 2. Body condition was evaluated during the first herd visit, sow dirtiness during the first and second visit. For each sow, the number of skin lesions on the body were counted and summed before entry into group-housing and again during the second visit from which the pre-grouping lesion score was subtracted to provide the number of lesions resulting from the post-grouping period (Geverink et al., 2009).

Table 2: Overview of the protocol to assess the floor and sow characteristics measured as possible risk factors for lameness development in sows

Risk factor	Method	Scoring system or unit	Location
Dirtiness	Visual assessment	Percentage of the floor that was covered with manure: <ul style="list-style-type: none"> - score 0: no manure on the floor → clean - score 1: 25% - score 2: 50% - score 3: 75% - 100% of the floor → very dirty 	Entire stable
Quality	Visual assessment	Quality of the floor: <ul style="list-style-type: none"> - score 0: Good quality flooring without any enlarged gaps, protruding objects or level differences between successive slats - score 1: presence of enlarged gap width - score 2: presence of protruding sharp objects - score 3: combination of score 1 and 2 	Entire stable
Wetness	Hygrometer(HM8-BF30, Merlin Technology GmbH)	Continuous (%)	at least every third of the dunging area and: <ul style="list-style-type: none"> - free access stalls: front and rear half of 10% of the stalls - other group-housing systems: in two random locations of each lying area and around every feeder and drinking valve.
Slipperiness	Portable Skid Resistance Tester (Munro Instruments Ltd.) with TRL rubber slider ^a	Continuous (British pendulum number) \approx coefficient of friction times 100	at least every third of the dunging area ^b
Body condition	Renco Lean Meter (Renco Corp.)	Backfat thickness (mm)	P2 position
Skin lesions	Visual assessment	Total number of skin lesions	Whole body (excluding the tail)
Sow dirtiness	Visual assessment (Welfare Quality®, 2009)	% of body soiled with manure: <ul style="list-style-type: none"> - score 0: <10% of the body → clean - score 1: 10 - 30% - score 2: > 30% → very dirty 	Both sides of the body

^a At each herd, the Skid Resistance Tester was calibrated.

^b At each point the mean of eight readings was taken; the floor was not cleaned before measurements were performed

5.3.3 DATA MANAGEMENT AND STATISTICAL ANALYSIS

Descriptive statistics were performed to assure data quality with respect to errors and missing values (SPSS 21.0, IBM Corp.). Continuous risk variables with suboptimal distribution and categorical risk variables with less than 10% of observations in one category were either redefined or categorized. Continuous and categorical variables retained for further analysis are summarized in Tables 3 and 4.

In order to examine the association between the possible risk variables and development of lameness during the first days in group-housing, multilevel logistic regression analysis was performed using the PROC GLIMMIX procedure (SAS 9.3, SAS Institute). Model building started with univariable evaluation of all possible risk variables mentioned in Tables 3 and 4. To account for the clustering of sows in the herd, a random herd effect was included. All independent variables with a significance value $P \leq 0.25$ were selected and used to build the multivariable model (Hosmer and Lemeshow, 2000). Before entering the variables into a multivariable model, correlations between the independent variables were tested (Spearman's rank correlation coefficient). If correlation was $> |0.6|$ only one out of the two variables was selected. As all sows were clean during the first herd visit, only sow dirtiness as scored during the second visit was included in the model. A manual stepwise backward model building procedure was followed and all variables with a P-value < 0.05 were retained in the final model. All two-way interactions between significant variables were assessed. During the stepwise backward procedure, changes in the estimated coefficients of the variables were checked to evaluate for confounding. The fit of the model was evaluated by inspection of the herd level standardized residuals plotted against the normal scores and against the herd-level predicted values (Dohoo et al., 2009).

Table 3: Description (means \pm standard deviation (S.D.)) of continuous variables concerning lameness development within the first days of group-housing in 810 group-housed sows from 15 Belgian pig herds and results of the univariable analyses with lameness development (yes/no) as dependent variable and herd as random effect.

Variable	Total		Lame		Non-lame		OR ^b (CI ^c)	P-value
	Mean \pm S.D.	Range	Mean \pm S.D.	n ^a	Mean \pm S.D.	n ^a		
Sow related								
Backfat thickness	14.7 \pm 3.7	7.0 – 30.0	15.3 \pm 3.7	106	14.6 \pm 3.7	704	1.05 (1.00 – 1.11)	0.058*
Skin lesions	14 \pm 17	0 – 115	17 \pm 20	106	14 \pm 16	704	1.01 (1.00 – 1.02)	0.073*
Herd related								
Herd size (nb of sows)	477 \pm 178	144 – 750	-	106	-	704	0.72 (0.56 – 0.94)	0.015*
Total area/sow (m ²)	2.3 \pm 0.27	1.67 – 3.0	-	93	-	628	0.23 (0.08 – 0.65)	0.005*
Solid area/sow (m ²)	0.96 \pm 0.48	0 – 1.65	-	93	-	628	0.53 (0.23 – 1.23)	0.138*
Flooring gestation unit:								
Slipperiness (Bpn) ^d	88.0 \pm 37.1	29.0 – 147.0	-	81	-	507		0.464
Wetness (%)								
lying area	2.3 \pm 0.91	0.95 – 5.20	-	81	-	583	0.80 (0.59 – 1.07)	0.130*
walking area	2.6 \pm 0.68	1.50 – 4.50	-	92	-	575		0.463

* Variables included in the multivariable logistic regression model

^a number of sows for which data were available, ^b Odds ratio, ^c Confidence interval, ^d British Pendulum number

Table 4: Description of categorical variables concerning lameness development within the first days of group-housing in 810 group-housed sows from 15 Belgian pig herds and results of the univariable analyses with lameness development (yes/no) as dependent variable and herd as random effect.

Variable	n	Sows		OR ^a (95% CI ^b)	P-value
		Lame n (%)	Non-lame n (%)		
Parity					
<i>0-1st parity</i>	298	49 (46.2)	249 (35.4)	ref.	0.043*
<i>2nd</i>	130	8 (7.5)	122 (17.3)	0.32 (0.15 – 0.71)	
<i>3rd-5th</i>	282	36 (34.0)	246 (34.9)	0.70 (0.40 – 1.22)	
<i>≥ 6th</i>	100	13 (12.3)	87 (12.4)	0.70 (0.33 – 1.47)	
Breed^c					
<i>PIC</i>	152	18 (17.0)	134 (19.0)		0.255
<i>Topigs 20</i>	187	33 (31.1)	154 (21.9)		
<i>Dalland</i>	196	19 (17.9)	177 (25.1)		
<i>Danbred</i>	93	12 (11.3)	81 (11.5)		
<i>JSR</i>	98	15 (14.2)	83 (11.8)		
<i>other</i>	84	9 (8.5)	75 (10.7)		
Sow dirtiness					
<i>< 10% dirt</i>	515	52 (57.1)	463 (69.7)	ref.	0.017*
<i>≥ 10% dirt</i>	240	39 (42.8)	201 (30.3)	1.73 (1.10 – 2.70)	
Herd type					
<i>farrow-to-finish herd</i>	430	58 (54.7)	372 (52.8)		0.463
<i>farrowing herd</i>	380	48 (45.3)	332 (47.2)		
Group-housing					
<i>FAS^d</i>	377	43 (40.6)	334 (47.7)	ref.	0.158*
<i>ESF^e</i>	119	21 (19.8)	98 (13.9)	1.90 (0.86 – 4.17)	
<i>Vario-mix and ad lib.</i>	100	10 (9.4)	90 (12.8)	0.65 (0.18 – 2.36)	
<i>Trough feeding</i>	214	32 (30.2)	182 (25.9)	1.69 (0.90 – 3.17)	
Origin gilts					
<i>Rearing</i>	505	54 (50.9)	451 (64.1)	ref.	0.010*
<i>Purchasing</i>	305	52 (49.1)	253 (35.9)	1.80 (1.15 – 2.81)	
Feeding strategy at rearing					
<i>ad libitum</i>	294	40 (37.7)	254 (36.1)		0.741
<i>restricted</i>	516	66 (62.3)	450 (63.9)		

Table 4: Continued

Variable	n	sows		OR ^b (95% CI ^c)	P-value
		Lame n (%)	Non-lame n (%)		
<i>Level</i>					
Group size					0.006*
≤ 15	361	38 (35.8)	323 (45.9)	ref.	
16-30	240	27 (25.5)	213 (30.3)	1.08 (0.64 – 1.82)	
> 30	209	41 (38.7)	168 (23.9)	2.07 (1.28 – 3.35)	
Flooring of gestation unit					
- Quality					0.254
<i>good</i>	468	59 (55.7)	409 (58.1)		
<i>bad^f</i>	342	47 (44.3)	295 (41.9)		
- Dirtiness (% soiled)					0.482
0%	91	10 (9.4)	81 (11.5)		
25%	300	45 (42.5)	255 (36.2)		
50%	252	32 (30.2)	220 (31.3)		
≥ 75%	167	19 (17.9)	148 (21.0)		
Cleaning of gestation unit					
once a year	256	40 (37.7)	216 (30.7)	ref.	0.107*
regular, dry	277	39 (36.8)	238 (33.8)	0.92 (0.48 – 1.80)	
regular, wet	179	17 (16.0)	162 (23.0)	0.47 (0.22 – 1.00)	
regular, wet + disinfection	98	10 (9.4)	88 (12.5)	0.50 (0.22 – 1.15)	
Water supply					
<i>ad libitum</i>	438	58 (54.7)	380 (54.0)		0.887
<i>restricted</i>	372	48 (45.3)	324 (46.0)		

* Variables included in the multivariable logistic regression model

^a Odds ratio, ^b Confidence interval, ^c breed represented by > 60% of the sow population, ^d Free Access Stalls, ^e Electronic Sow Feeders, ^f presence of enlarged gaps and protruding objects

5.4 Results

5.4.1 DESCRIPTIVE

The first four weeks of gestation, sows were housed in the individual stalls of the insemination stable. In 12 of the 15 herds, sows were housed on partially slatted concrete floors. In the other three herds, the partially slatted floors consisted of a concrete solid area in combination with metal slats. Four weeks after insemination, sows were moved to the group-housing. Group size within each herd ranged from 9 to 90 sows (median = 19 sows). The mean floor space allocated per gestating sow was 2.3 m² with a minimum of 1.67 m² and a maximum of 3.0 m². All herds had solid concrete flooring in the lying area and concrete slatted flooring in the dunging area of the gestation unit. Only one herd used triangular metal slats. In 80% of herds, flooring in group-housing was of good quality but in more than half of the herds (53%), floors were moderately to severely soiled (median dirtiness score = 2). Grip of dunging areas differed highly between herds with a minimum slip-resistance of 29 and a maximum of 147 (mean = 87.7) British pendulum number. Lying areas were in general slightly drier (mean wetness score (SD) = 2.3 (0.91)) than dunging areas (mean wetness score (SD) = 2.6 (0.68)), but for both areas, wetness varied strongly between herds.

A total of 827 sows were examined, however two sows could not be followed-up due to repeat breeding. Fifteen sows were excluded from the study because they were already lame before transfer to group-housing. The remaining 810 animals had farrowed on average 2.7 (0 – 12) times and had a mean (SD) backfat thickness of 15 (3.7) mm. After three to five days of group-housing, 32% of the sows was moderately to severely covered with manure and 73% suffered from skin lesions with on average 18 (1 - 115) lesions per sow. The frequency distribution of skin lesions showed a positive skew (skewness = 2.0). The prevalence of dirty sows (> 10% of body soiled) varied between herds with a median of 26% (8.1 – 64.3) across all herds. In total, 106 sows (13.4%) developed lameness within the first three to five days of group-housing and of these, 24 sows (3% of the total) were severely lame. Across all herds, a median of 13.1% (0 – 27.3) of the examined sows developed lameness within the first days of group-housing.

5.4.2 MODEL

The following variables were associated with lameness in the univariable analyses ($P \leq 0.25$, Table 3 and 4) and were included in the multivariable model: parity, backfat thickness, skin lesions, sow dirtiness, herd size, type of group-housing, origin of gilts, group size, total and solid area available per animal, wetness of lying area and cleaning. Due to the high correlation ($\rho = 0.64$; $P < 0.001$) between the variables 'total area per sow' and 'wetness of lying area', wetness of lying area was, in view of practical relevance, not included in the multivariable model. Table 5 shows the final multivariable logistic regression model. Dirty sows with >10% of the body covered with manure had significantly higher odds (OR: 2.33 (1.42 – 3.85); $P < 0.001$) for lameness development compared to clean sows. An increase in floor area per sow from 1.67m² to 3.0m² (OR: 0.40 (0.17 – 0.95); $P = 0.031$) and in herd size from 144 to 750 sows (OR: 0.71 (0.54 – 0.95); $P = 0.020$) decreased the odds of lameness development. None of the two-way interactions between the remaining variables was significant ($P > 0.05$). Confounding factors were not found throughout the model building procedure.

Table 5: Final multivariable logistic regression model, with herd as a random effect, for risk factors for lameness in group-housed sows from 15 randomly selected herds.

Variable	Categories	n _{sows}	n _{herds}	b ^a (se)	OR ^b (95% CI ^c)	P value
Sow dirtiness	< 10% dirt	515	14	ref.		
	≥10% dirt	240	14	0.85 (0.25)	2.33 (1.42 – 3.85)	0.001
Herd size (number of sows)		810	15	-0.34 (0.14)	0.71 (0.54 – 0.95)	0.020
Total floor area/sow (m ²)		721	14	-0.93 (0.43)	0.40 (0.17 – 0.92)	0.031

^aRegression coefficient, ^bOdds ratio, ^cConfidence interval

5.5 Discussion

The mean incidence of lameness development (13.4%) within the first days of group-housing found in this study was higher than the incidence observed by Kroneman et al. (1993). Albeit restricted to the population of Belgian herds, the external validity of the result found in this study is likely higher as it was based on data from 15 herds whereas the study by Kroneman et al. (1993) was based on data from one herd. Because lameness is a condition associated with pain and discomfort, it is important that group-housing systems are designed and managed so that the lameness incidence is diminished and welfare of sows is guaranteed. In the current study, focus was on risk factors for lameness development within the first days after sows were moved to the group-housing.

An increase in herd size from 144 sows to 750 sows lowered the odds for developing lameness. The percentage of sows that developed lameness decreased logarithmically with increasing herd size without the presence of a clear cut threshold value. Herd size was significantly correlated with group size, but the Spearman's rank correlation coefficient was rather low ($\rho = -0.38$; $P < 0.001$). Group size was not retained in the final model which may suggest that group size in the present herds did not influence the relationship between herd size and lameness development. The decreasing odds for lameness with increasing herd size may be explained by improved management with increasing herd size. On some herds, measures (e.g. locking up sows the first days of group-housing in case of free access stalls and the use of odorous sprays when moved to group-housing) were taken to minimize post-grouping aggression. These management practices were however not included in this study. A high correlation ($\rho = -0.58$; $P < 0.001$) was found between herd size and the origin of the breeding gilts indicating that large herds reared their own gilts rather than purchasing new gilts. Purchasing breeding gilts was in the univariable analysis significantly associated with a higher odds (OR: 1.80 (1.15 – 2.81); $P = 0.01$) for lameness development compared to rearing own breeding gilts. Rearing management has indeed been reported to be important to control premature disposal of sows due to lameness (Gill, 2007). The results of the present study can indicate that rearing own breeding gilts may promote the development of sound feet and legs.

Sows also benefited from an increase in floor space allowance from 1.67m² to 3.0m². The minimal floor space requirements for gestating sows are regulated by law (European Commission, 2008). All sows in this study were housed according to these recommendations, except for one herd. The incidence of lameness in this herd was however lower than the

median of 13.1%, indicating also other factors have been of influence. However, the optimal area per sow could not be defined based on the results of the present study.

Sows with more than 10% of the body covered with manure had a higher risk to develop lameness compared to clean sows (< 10% of body surface dirty). An association between sow dirtiness and lameness has been suggested previously in a study by Zurbrigg and Blackwell (2006), but it was not scientifically proven. The strong significant association between dirtiness and lameness may imply that dirtiness can be an indirect indicator of welfare. Sow dirtiness as a measure of welfare has indeed been suggested previously (Geverink et al., 2009). What caused the increased amount of manure on the body of lame sows remains unclear. Because all sows were scored clean during the first herd visit, it can be assumed that sow dirtiness, as included in the model, resulted from housing in the gestation unit (*i.e.* group-housing). Lame sows are less active, have shorter standing times and explore less compared to non-lame sows (Madec et al., 1986; Valros et al., 2009). It is possible that lame sows become dirtier because they lay down more often. However, data on sow behaviour were not recorded during the first three to five days of group-housing. The highest percentage of dirty sows was found on the herds with the highest floor dirtiness score ($\rho = 0.612$; $P < 0.05$). Nevertheless, floor dirtiness was not retained in the model which may indicate that soiling of the floor probably did not cause a higher odds for lameness. No significant interaction was found between sow dirtiness and the floor area per sow what suggests that floor space allowance neither influenced the association between lameness and sow dirtiness.

Surprisingly, none of the floor characteristics measured in this study had a significant effect on the development of lameness within the first days of group housing. Minor deficiencies in flooring quality were only found in two herds. The general good quality of flooring in the herds in this study probably was the reason why no association between quality and lameness development could be detected. Slipperiness of the floor differed strongly between herds. To the authors' knowledge, this is the first time since the study of Penny et al. (1965) that slipperiness of sow pen floors was measured quantitatively on commercial herds. In the present study, three herds had a slip-resistance less than the recommended minimum of 0.63 (Thorup et al., 2007) whereas on five herds a slip resistance exceeded the advised maximum of 0.84 (Penny et al., 1965). Yet, significance of slipperiness may have been undetectable due to the fact that only a short term effect of flooring was evaluated. The short timeframe also could have contributed to the lack of a significant effect of wetness and dirtiness of the floor surface.

Similar to the results of Turner et al. (2006), a wide phenotypic variability in skin lesion score was found, in which a disproportionate amount of skin lesions were present on a minority of sows. The number of skin lesions has been associated with the number of aggressive interactions following grouping of sows (Barnett et al., 1992). The variable ‘skin lesions’ was not retained in the final model. Aggressive encounters between sows therefore was not a risk factor for lameness development within the first days of group-housing in the present herds.

An advantage of observational studies is that animals are observed in their natural setting which results in a higher external validity compared to experimental study designs. Many factors may have differed between sows and between herds. In this study, focus was on housing conditions and post-grouping aggression. However, other factors that were not included in this study such as rearing management practices and measures to reduce post-mixing aggression, may have played a role. This study has revealed associations between various contributory factors and lameness development but further research is necessary to identify the specific causes.

5.6 Conclusions

The estimated incidence of lameness in gestating sows developed within the first days of group-housing was 13.4%. The results showed that within the first days of group-housing, sow dirtiness is a possible proxy indicator of lameness, and that an increase in floor space allowance and herd size may diminish lameness development. Yet lameness development did not appear to be influenced by injurious aggressive encounters among sows or floor characteristics. To prevent sow lameness shortly after introduction into the group, the relationship between herd size and sow dirtiness on the one hand and lameness development on the other hand needs to be further explored. The optimal floor space allowance requires further research and should reveal whether the EU recommendations suffice to control lameness in group-housed sows. In future field research the role of both rearing management practices and measures to reduce aggression should be clarified.

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Appendix

Questionnaire concerning general herd characteristics as well as housing conditions, management and feeding and water provision practices of the insemination and gestation unit filled in by the farmer. Answers were run through by the first author through face-to-face interviews of the pig farmers and inspection of the stables.

Vragenlijst Veehouder

Adresgegevens:

Naam:

Adres:

Tel.:

Fax.:

E-mail:

ALGEMEEN

Aantal productieve zeugen aanwezig op het bedrijf:.....

Soort bedrijf:

- Gesloten bedrijf
- Vermeerderingsbedrijf
- Andere

Type groepshuisvesting op het bedrijf:

- Voerligboxen met vrije uitloop
- Groepshuisvesting met voederstations
- Groepshuisvesting met ad libitum voeding
- Andere:.....

Type groep:

- Dynamisch
- Statisch

Type van groepsgewijs managementsysteem:

- 1-weeksysteem
- 2-wekensysteem
- 3-wekensysteem
- 4-wekensysteem
- 5-wekensysteem

Leeftijd waarop gespeend wordt:

Meest gebruikte zeugenras op het bedrijf

- PIC
- Hypor
- Topigs 20
- Dalland
- Danbred
- Rattlerow-Seghers
- JSR
- Frans Hybride
- Eigen rotatiekruisingen
- Andere

Aanvoer van gelten op het bedrijf:

- Eigen opfok
- Aankoop
- Combinatie eigen opfok en aankoop

Op welke leeftijd worden gelten aangekocht?

.....

Gebeurt aankoop vanuit het buitenland?

- Ja (vermeld oorsprong)
- Neen

HUISVESTING

Huisvesting van jonge gelten igv eigen opfok:

- Vanaf wanneer worden opfokgelten afgezonderd van de vleesvarkens?

.....

- type ventilatie:

- Deurventilatie (*frisse lucht komt via een opening in de deur de stal binnen*)
- Plafondventilatie (*frisse lucht komt via openingen in een vals plafond binnen in de stal*)
- Combiventilatie (*een gemodificeerde versie van plafondventilatie: gleuf in plafond boven de centrale gang*)
- Klepventilatie (*frisse lucht komt via kleppen in de wand of het plafond de stal binnen*)
- Gangventilatie (*frisse lucht komt vanuit een ruimte onder de stal via roosters in de loopgang bij de dieren*)
- Frisse neuzensysteem (*frisse lucht komt binnen langs de kop vd zeug*)

- Hoe wordt de stal gereinigd en ontsmet? (productnamen, droog/nat reinigen?, voorweken?, warm water? Leegstand? En hoe frequent?)

.....
.....

- Wanneer (leeftijd; bij 1ste of 2e bronst) worden de gelten verplaatst naar de dekstal?

.....

- Worden de gelten tussen de opfokstal en de dekstal nog elders gehuisvest bv. voor bronststimulatie?

- Neen
- Ja

Huisvesting van de zeugen in de quarantainestal:

- type ventilatie (voor definities, zie opfok):

- Deurventilatie
- Plafondventilatie
- Combiventilatie
- Klepventilatie
- Gangventilatie
- Frisse neuzensysteem

- Hoe wordt de stal gereinigd en ontsmet? (productnamen, droog/nat reinigen?, voorweken?, warm water? Leegstand? En hoe frequent?)

.....
.....

Huisvesting van de zeugen in de dekstal:

- worden de zeugen na het spenen in groep gehuisvest?

- Neen
- Ja → hoe lang?

- type voerbak:

.....

- type ventilatie:

- Deurventilatie
- Plafondventilatie
- Combiventilatie
- Klepventilatie
- Gangventilatie
- Frisse neuzensysteem

- Hoe wordt de stal gereinigd en ontsmet? (productnamen, droog/nat reinigen?, voorweken?, warm water? Leegstand? En hoe frequent?)

.....
.....
.....

- hoeveel dagen na het insemineren worden de zeugen verplaatst naar de drachtstal?

.....

Huisvesting van de zeugen in de drachtstal:

- Worden drachtige zeugen en gelten samen gehuisvest?

- Ja
- Neen

- Indien drachtige gelten afzonderlijk worden gehuisvest, vermeld hun manier van huisvesting:

- Individuele zeugenboxen met partieelrooster
- Voerligboxen met vrije uitloop
- Groepshuisvesting met voederstation
- Groepshuisvesting met ad libitum voeding
- Andere:

- Hoe lang worden de gelten afzonderlijk gehuisvest?

- De eerste maand van de dracht
- De volledige dracht
- Andere:.....

- type ventilatie:

- Deurventilatie
- Plafondventilatie
- Combiventilatie
- Klepventilatie
- Gangventilatie
- Frisse neuzensysteem

- Hoe wordt de stal gereinigd en ontsmet? (productnamen, droog/nat reinigen?, voorweken?, warm water? Leegstand? En hoe frequent?)

.....
.....
.....

- Hoeveel dagen vóór het werpen, worden drachtige zeugen verplaatst naar de kraamstal?
.....

Huisvesting van de zeugen in de kraamstal:

- type ventilatie:

- Deurventilatie
- Plafondventilatie
- Combiventilatie
- Klepventilatie
- Gangventilatie
- Frisse neuzensysteem

- Hoe wordt de stal gereinigd en ontsmet? (productnamen, droog/nat reinigen?, voorweken?, warm water? Leegstand? En hoe frequent?)
.....
.....

AFVOERBELEID

% zeugen dat werd afgevoerd het afgelopen jaar:.....

Gemiddelde leeftijd van de afgevoerde zeugen:.....

Afvoerbeleid met betrekking tot kreupele zeugen:

- kreupele dieren worden niet behandeld maar meteen afgevoerd
- kreupele dieren worden eenmalig behandeld (geen herstel=afvoer)
- kreupele zeugen worden verschillende malen behandeld (geen herstel=afvoer)
- kreupele zeugen na spenen worden afgevoerd, kreupele dieren op een ander moment in de cyclus tracht men te behandelen
- andere:

VOEDER en DRINKWATER

Voederstrategie tijdens opfok:

- Ad libitum*
- Beperkt

Welk type voer wordt aan opfokgeltjes gegeven? (opfok-,dracht-, vleesvarkensvoer)?

.....

Hoeveel maal per dag krijgen de dieren voeder?

.....

Hoeveel voer wordt gemiddeld per opfokzeug voorzien?

.....

Worden er supplementen gevoerd aan de opfokzeugen?

- Neen
- Ja:
 - °Welke:.....
 - °Hoeveel:.....
 - °Welke periode:.....

Zijn er reeds problemen met het beenwerk in de quarantaine of in de opfokstal zichtbaar?

- Neen
- Ja → welke:

Voederstrategie tijdens de dracht:

- Vlak voederschema
- Opbouwend voederschema

Hoeveel maal per dag wordt er gevoerd in de dracht?

.....

Hoeveel kg voeder wordt gemiddeld per zeug gevoerd tijdens de dracht (schema bijvoegen)?

.....

Worden er supplementen gevoerd aan de drachtige zeugen?

- Neen
- Ja:
 - °Welke:.....
 - °Hoeveel:.....
 - °Welke periode:.....

Wanneer wordt er overgeschakeld van drachtvoer naar lactatievoer:

- Bij het verplaatsen van de zeugen van de drachtstal naar de kraamstal
- Zodra de zeugen hebben geworpen
- Andere:

Voederstrategie in de kraamstal:

- Vlak voerschema
- Opbouwend voerschema

Hoeveel maal per dag wordt er gevoerd in de kraamstal?

.....

Hoeveel kg voeder wordt gemiddeld per zeug gevoerd tijdens de lactatie (schema bijvoegen)?

.....

Worden er supplementen gevoerd aan de lacterende zeugen?

- Neen
- Ja:
 - °Welke:.....
 - °Hoeveel:.....
 - °Welke periode:.....

Type drinkwater dat gebruikt wordt:

- Boorputwater
- Oppervlaktewater
- Drainagewater
- Water van het openbare leidingnet
- Hemelwater
- Open put water
- Andere:.....

Recente drinkwateranalyses?

- Neen
- Ja → bijvoegen

Waternverstrekkning (omcirkel wat past):

Continu: dracht – lactatie- dekstal

Beperkt (vermeld hoe vaak/lang): dracht- lactatie- dekstal

VACCINATIE en MEDICATIE

Vaccins op het bedrijf

Welke

Wanneer toegediend

.....
.....
.....

Preventieve medicatie in voer/drinkwater?

Wat

Wanneer

Reden

.....
.....

Ontwormingsschema (wat en wanneer)

Zeugen:.....
.....

Vleesvarkens:.....
.....

Gezondheidsstatus:

- Schurftvrij? Ja Nee
AR(Snuffel)vrij? Ja Nee
PRRSVvrij? Ja Nee

- Problemen nu aanwezig op het bedrijf? Wordt hiertegen behandeld? Waarmee en hoelang?
.....
.....

Wat is uw mening over het evt. gebruik van voetbaden met formol voor zeugen ter preventie van klauwproblemen? Heeft u reeds ervaring met deze methode? (naar analogie met wat gedaan wordt bij rundvee)

.....
.....
.....

BRONST – en SPEENMANAGEMENT

Bronstdetectie

- Vanaf welke dag na het spenen start bronstdetectie:.....dagen

- Hoe veel maal per dag wordt bronst gecontroleerd:.....

- Hoe gebeurt de bronstdetectie:

- Beer wordt voor de zeugen geplaatst; de beer wordt dus verplaatst
 Zeugen worden voor de beer geplaatst; de zeugen worden dus verplaatst

- wordt 3 weken na het dekken opnieuw bronst gecontroleerd?

- Ja
 Neen

- Hoe gebeurt deze bronstcontrole:

- Beer wordt voor de zeugen geplaatst; de beer wordt dus verplaatst
 Zeugen worden voor de beer geplaatst; de zeugen worden dus verplaatst

- Hoe gebeurt het spenen?

- Zeugen worden verplaatst naar de dekstal en biggen blijven nog (invullen) dagen zitten in het kraamhok
- Zeugen worden verplaatst naar de dekstal en biggen diezelfde dag naar de batterij

Te verzamelen formulieren

Bedrijf- en cyclusoverzicht: uitdraai technische resultaten

Samenstelling voeder tijdens de opfok (etiket)

Samenstelling van het drachtvoer (etiket)

Schema voederstrategie tijdens de dracht

Samenstelling van het lactatievoeder (etiket)

Schema voederstrategie in de kraamstal

Eventuele uitslag van recente (< 1jaar) drinkwateranalyse

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6.1 Introduction

From a welfare and economic point of view, prevention of lameness in group-housed gestating sows is required. A decline in the prevalence of sow lameness by using proper preventive strategies may improve animal welfare, enhance farmer's working pleasure and diminish financial loss, all of which may contribute to a more sustainable pig production.

The major aim of the thesis was to improve the prevention of lameness in group-housed gestating sows by refining lameness detection, investigating the impact on reproductive performance and identifying risk factors. The present chapter discusses the development of a more objective detection method, the direct impact of lameness on the sow's reproductive performance and the results of the risk factor analysis with regard to potential preventive measures. A schematic representation of the knowledge acquired at the end of this thesis is shown in figure 1.

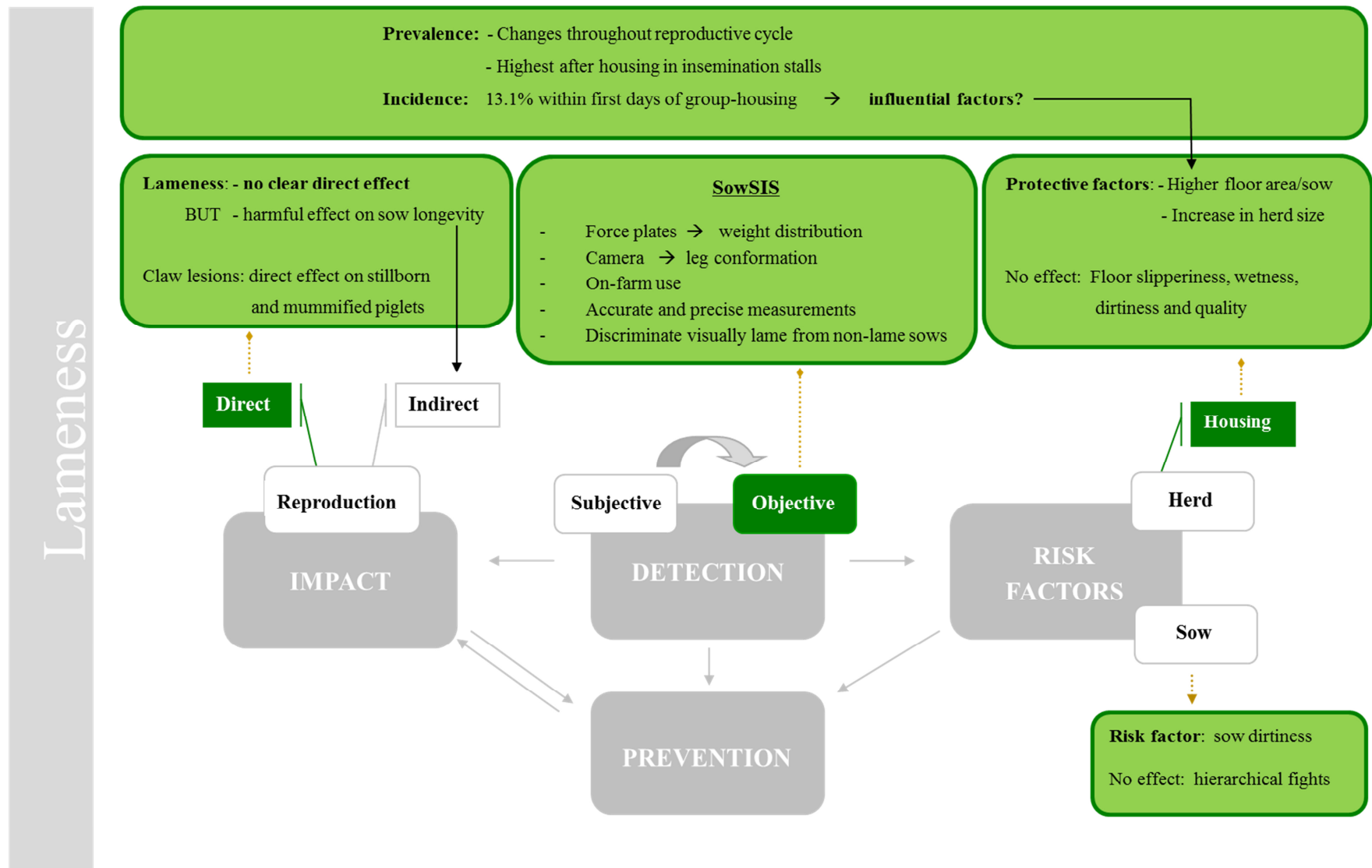


Fig. 1. Schematic representation of the acquired knowledge at the end of this thesis

6.2 Sow lameness detection - SowSIS

Reliable methods to detect lameness are of paramount importance to identify lame sows that need treatment, to make a correct estimation of on-farm lameness prevalence and to perform proper risk factor analysis. Within the framework of evidence-based medicine, accurate lameness detection is also a prerequisite to evaluate the effectiveness of remedial measures and to develop successful preventive strategies. So far, lameness detection in sows has been restricted to visual methods which are cheap and easy to perform but are characterized by high inter-observer variability. More objective, precise and sensitive detection methods may be helpful to improve the diagnosis. Therefore, a lameness detection system based on force and visual stance variables derived from balance analysis and image processing respectively, was developed: SowSIS (Sow Stance Information System) (**chapter 3**).

The developed system proved to be **highly accurate** ($R^2 \approx 1$) for measuring weight, irrespective of the position of the mass relative to the load cell and the duration of measurements. The accuracy of SowSIS when measuring joint angles has yet to be established. Sow mobility within the device is limited, but the sows still have enough decimetres of forward, backward and sideways movement available to permit accurate calculation of joint angles. The accuracy of the visual stance variables, measured at different distances and angles to the camera, can be determined using a pig skeleton with known joint angles. Understanding the impact of the skeleton's position to the camera on the angle measurements will contribute to an accurate estimation of joint angles in live animals. As an alternative, also a sow's hind leg with the anatomical reference points being marked on it, can be used. So far reference points have been marked using a wax-based marker. For practical reasons, instead small circular, adhesive markers will be used in future research. These markers are attached to the skin and repeatability of positioning greatly depends on the correct palpation of the anatomical reference points. Marker movement can be biased by skin displacement away from the underlying reference point (Clayton and Schamhardt, 2013). Correction models have been described for horses (Van Weeren et al., 1992) but are not yet available for pigs. To ensure accuracy of visual stance variables, also the correct positioning of these markers has to be evaluated.

SowSIS permitted adequate registration of force and visual stance variables with a **sufficient level of precision** ($CV \leq 15\%$) in visually non-lame sows. The high repeatability of the three visual stance variables demonstrated their potential to objectively assess a sow's standing

posture. Force stance variables also proved to be repeatable except for the number and duration of both kicks and weight shifts which showed high within-animal variability. In dairy cattle, repeatability of visually observed kicks has been reported to differ according to the definition. Lifting a leg less than 15 cm was found to be highly repeatable whereas raising a leg at least 15 cm was less repeatable (De Rosa et al., 2003; Napolitano et al., 2005). However, SowSIS does not make a distinction in height when measuring kicks. The number of kicks and weight shifts in cattle, measured using a four-balance system installed into a milking robot, have been reported to be associated with the cow's behavioural response to humans (Rousing et al., 2004; Napolitano et al., 2005), by restlessness (Pastell et al., 2006), head movements (Neveux et al., 2006), disturbances in the environment (Ordolff, 1991) and duration of measurements (Chapinal et al., 2011). It may be possible that the sows in our study became restless in course of the five consecutive measurements. As measurements were performed in the central corridor of the stable and near a feed silo, it is possible that sows were sometimes distracted by the sound of feed dropping or by passage of other people, affecting restlessness and head movements. All these factors may have contributed to the variability in kicks and weight shifts between repeated measurements.

The developed system **detects lameness** in sows **while standing**. However, Kilbride et al. (2009) reported that 57% of the pregnant sows with an abnormal gait had a normal leg weight distribution when standing at visual inspection. Studies in cattle revealed that sometimes lame cows could not be detected based on leg weight distribution measures while standing (Pastell et al., 2010). Balances measuring leg weight distribution while standing have furthermore been reported to be able to detect claw-related lameness whereas lameness due to joint problems may be missed (Kujala et al., 2008). Lameness detection using SowSIS however is not only based on leg weight distribution measures. The system also calculates joint angles to assess the sow's standing posture. Leg conformation traits such as upright pasterns and steep hock joints have been associated with claw lesions and osteochondrotic joint changes (Jørgensen, 2000). Both conditions are an important cause of sow lameness (Heinonen et al., 2006; Nielsen and Haugegaard, 2012). Consequently, information on the sow's standing posture derived from the visual stance variables compensates for the limitations of the balance analysis.

Notwithstanding, the combination of SowSIS and dynamic assessment could be studied in future research. Kinematic techniques are not appropriate for on-farm application due to their complicated set-up and expensive equipment while force plates often require many passages

before a sufficient number of valid strides are recorded. Pressure plates however, could be an option. The advantage of pressure-sensitive walkways is that they simultaneously provide information on the force exerted on each leg as well as on the pressure distribution under each claw. Yet, the implementation of dynamic pressure-based gait analysis requires a place in the stable where sows must often walk through during the day, as part of their routine. So far the number of sow herds having a setting that lends itself to build in the pressure plate (*e.g.* corridor for walk-through selection after leaving the feeding station), are scarce.

The study in **chapter 3** of this thesis showed that force stance variables acquired with SowSIS were able to **discriminate non-lame from unilateral lame** sows. Especially the relative weight exerted by a leg, leg weight symmetry and the number of kicks and weight shifts appeared to be good indicators of sow lameness. The same variables have already been demonstrated to have potential for the detection of lameness in dairy cattle (Pastell and Kujala, 2007; Pastell et al., 2008).

The developed system also proved its **practical** use in research settings. The demountable concept made it possible to mount the device almost anywhere in a stable without problems of carrying it through small corridors and around sharp turns. All parts of the device can be easily carried (± 10 kg) by one person except for the frame with the four load cells (± 80 kg). The length of the camera arm could restrict position of the device as a distance of at least 0.960 m is required at both sides of the box to take images of the hind legs. Nevertheless, on both herds where the device was used, a suitable position could be found, *i.e.* broad enough to set up the device and close to the gestation stable. For application on-farm as a management tool, SowSIS measurements will have to be automated and the device should be built in, *e.g.* at the drinking bowls or in a feeding station. A five-minute measurement period was chosen to confirm that enough usable data were collected for each evaluation. Nonetheless, further research should determine the optimal measurement duration as well as the time needed for a sow to adapt to the device.

Despite the promising features of the developed system, there are still some improvements to be made.

Head movements may have influenced force stance variables. Sows attempted to peer outside through the space between the side panels or the upper edge of the box when hearing the sound of feed dropping from the silos or when people passed the device. Sows also moved their head from side to side while searching for concentrate that was provided in the front part

of the box. These head movements may have influenced leg weight distribution between both front legs as well as between the front and hind legs. To limit the sow's peripheral view and ability to move the head, the front half of the device may be equipped with lateral blinders. Concentrate and straw could be provided in a feeding trough attached to the centre of the door. However, a reduction in the weight exerted on the front legs due to resting the jaw on the feeding trough should also be avoided. By using an additional camera on top of the device, the impact of head movements on the variability of the stance variables can be quantified. Understanding the impact of head movements will improve sensitivity and specificity of lameness detection based on stance variables.

SowSIS is able to distinguish non-lame from unilaterally lame sow, yet detection of **bilateral lameness** may be challenging. When lame in one leg, animals redistribute weight from the affected leg primarily to the contralateral leg and increase weight shifting between the contralateral legs while standing (Rushen et al., 2007; Karriker et al., 2013). These changes may be less obvious when animals are lame in both front and rear legs. Standing cows that encountered discomfort in both front legs were reported to shift some weight to the rear legs. However, discomfort in both rear legs may not lead to apparent changes in leg weight symmetry or the number of weight shifts (Neveux et al., 2006). Adding information about *e.g.* kicking behaviour may improve lameness detection. When detection was based on leg weight asymmetry, weight shifting as well as kicking, bilateral lameness could be detected in cattle although detection was still slower than for a unilateral problem (Kujala et al., 2008). Further research is needed to identify the changes in force and visual stance variables that are indicative of bilateral lameness in sows. Experimental lameness induction as described by Karriker et al. (2013) could be used for this purpose.

Although cheaper compared to dynamic lameness detection systems, SowSIS in its present form is an **expensive** investment. Installing the four load cells and guppy camera into an electronic feeding station may offer the possibility for automatic and repeated measurements of the force and visual stance variables reducing labour costs and the costs associated with building the demountable box. The expensive tablet PC (2500 €) can be replaced by driving the software on the same central PC that coordinates the automatic feeding stations. The four load cells (4 × 1000 €), guppy camera (750 €) and lens (200 €) will remain the major cost items. However, large scale production and positive evolution in price of camera and lenses may lower these costs.

6.3 Towards lameness control and prevention

Proper recognition of lame sows, preferably at an early stage, is definitely indispensable for proper lameness control and prevention, but accurate detection alone does not suffice to tackle this disease condition. Working towards a reduction in sow lameness also requires motivation of the farmer and knowledge on the risk factors for lameness.

6.3.1 ECONOMIC IMPLICATIONS AS MOTIVATOR TO CONTROL AND PREVENT LAMENESS

To encourage farmers to reduce lameness, it is necessary to understand the barriers that restrict farmers' efforts in lameness prevention as well as the motivating factors that drive their efforts. Studies on lameness in dairy cattle revealed that the economic implications of lameness are potentially powerful drivers. Economic losses related to sow lameness can be attributed to higher veterinary costs, increased work load, a higher risk for total or partial condemnation at slaughter and an (in)direct impact on reproduction (Schutttert, 2008). However, farmers' limited awareness of these effects restricts the impact of financial profit as motivator of change (Leach et al., 2010a; Leach et al., 2010b). Clarification of the economic impact would likely augment efforts to reduce lameness in sows. To assess this impact, first the effect of lameness on reproduction has to be elucidated.

Results in this thesis (**chapter 4**) indicate that lameness affects the overall herd performance rather than the reproductive performance of individual sows and that the economic impact of sow lameness is largely determined by the **detrimental effect on sow longevity**. This means that as pig producers endeavour to minimize sow lameness, sow longevity will improve, the percentage of sows at peak production (parities three to five) will increase, the health risks related to introduction of new gilts will reduce and replacement and labour costs will decrease.

In **chapter 4** of this thesis, a clear **direct association** between the presence of **claw lesions and the farrowing performance** of sows was shown. This implies that claw lesions can directly affect sow productivity. Indeed, similar associations have been reported in previous studies (De Pita, 2010; Anil, 2011; Fitzgerald et al., 2012). However, although a significant association between claw lesions and sow reproduction has been demonstrated, causality could not be established. For example, the higher odds of having stillborn piglets in the

presence of white line lesions might also be explained because sows with stillborn piglets may have been more susceptible to white line lesions. Yet, the presence of a significant association between claw lesions and sow farrowing performance is surprising as a similar association was not found for lameness. It is possible that the claw lesions, which had an effect on sow reproduction, did not cause pain or discomfort and that sow lameness resulted from other reasons than claw lesions, such as joint disorders. This suggests that claw lesions can harm a sow's reproductive performance without lameness being present. Following this reasoning, not only lameness but also claw lesions should be monitored to maintain optimal reproductive performance of sows. Alternatively, it is possible that sows with claw lesions suffered from pain and discomfort but that lameness caused by these claw lesions was not detected during visual examination. Detection may have failed because sows having these claw lesions maybe suffered from bilateral lameness. Changes in gait and posture may be less clear in animals that are lame on both sides than in animals that are unilaterally lame. Also, it might be more difficult to detect such bilaterally lame animals using visual assessment. Following this argumentation, sows that are lame due to these claw lesions, may show impaired reproductive performance. If lameness would be detected, likely an association between lameness and sow reproductive performance would have been found.

Although **no clear direct effect** of lameness was found on sows' reproductive performance within the same cycle as lameness was scored, lameness may still have a direct effect on the reproduction results. In **chapter 4** only a single cycle was studied, commencing at weaning, whereas negative effects might be manifest in a subsequent cycle if consequent on lactation disorders.

6.3.2 RISK FACTORS FOR LAMENESS

Results of this thesis have demonstrated that the prevalence of sow lameness differs between herds and varies throughout the reproductive cycle (**chapter 4**). Hence, to determine the severity of a lameness problem in a herd, lameness should be assessed at different times throughout the reproductive cycle. Knowledge on the time at which lameness is most prevalent will enable a more targeted search for risk factors. In **chapter 4** of this thesis, the highest prevalence of lameness was found after housing sows for five weeks in the individual stalls of the **insemination stable**. This result suggests that housing in the insemination stable might increase the risk for developing lameness. In the insemination stable, sows are housed

in conventional stalls. Restricted mobility in stalls has been related with a deterioration of muscle conformation and bone strength as well as with lameness (Marchant and Broom, 1994; Karlen et al., 2007). However, these effects could only be demonstrated when sows were housed in stalls during almost the entire gestation period whereas in the herds studied, sows were housed in stalls for up to five weeks. Oestrus-induced restlessness and agitation when the boar walks along the stalls, may also implement a risk for injury. Dirty, wet floors could also predispose sows to lameness development. However, the floor of the insemination stalls was clean on every herd. The higher prevalence of lame sows may not be the result of risk factors associated with the period in the insemination stalls alone. It is possible that sows already become prone to lameness development during housing in the farrowing crates, *e.g.* due to the high physiological demands associated with lactation or due to other risk factors related to the farrowing period.

Surprisingly, the high prevalence of lame sows (8.1%) found after housing sows in the insemination stalls in **chapter 4** could not be confirmed in the study described in **chapter 5**. In **chapter 5**, only 1.8% of the sows (15 out of 826) were scored lame at that moment. The prevalence of lame sows after housing in the farrowing crates and at the end of group-housing was not determined in the study described in **chapter 5**. Therefore, the lameness prevalence after sows had been housed in the insemination stalls could not be compared with the prevalence at the other two stages in the reproductive cycle. Nevertheless, the very low prevalence found in **chapter 5** implies that housing in the insemination stable may not always be associated with the highest lameness prevalence.

Other researchers have reported that the occurrence of sow lameness may also change throughout the gestation period. The occurrence of lame sows can be expressed as either prevalence (*i.e.* the number of lame sows at a given moment) or incidence (*i.e.* the number of sows that develop lameness within a specified period) (Dohoo et al., 2009a). The highest incidence of lameness in group-housed sows has been demonstrated in the first two months of gestation while the highest prevalence of lameness has been found at the end of gestation (Kroneman et al., 1993; Díaz et al., 2013). The results in this thesis demonstrated a mean lameness prevalence of 5.1 % at the end of gestation (**chapter 4**) and a mean lameness incidence of 13.1 % shortly after introduction into group-housing (**chapter 5**). The lameness prevalence was lower compared to previous studies (Kroneman et al., 1993; Díaz et al., 2013). The difference between studies cannot be explained by differences in classification of lame sows. Diaz et al. (2013) used the same locomotion scoring system and cut-off to define lame

sows as in our study (**chapter 4** and **5**). It might be that the prevalence of lame sows at the end of gestation in commercial English pig herds is higher than in Belgian pig herds with a herd size of at least 750 sows. Kilbride et al. (2009) reported a similar high prevalence of lame gestating sows in herds in the United Kingdom. The lameness incidence found in **chapter 5** of this thesis was higher compared to an earlier study (Kroneman et al., 1993). Results found by Kroneman et al. (1993) were based on data from one herd whereas our results were based on data from 15 herds. Albeit restricted to Belgian pig herds, the external validity of the incidence found in this thesis is likely higher. Hence, to minimize sow lameness, research on preventive measures should also focus on the gestation period shortly after introduction into group-housing. Influential factors for lameness development within the first days of group-housing were investigated in **chapter 5** of this thesis.

Our results showed that group-housed sows may benefit from a **higher floor space allowance** (**chapter 5**). An increased floor space allowance, within the range of 1.67 to 3.0 m², significantly decreased the odds of lameness development within the first days of group-housing. The space requirements for sows can differ according to group stability, group size, pen design and feeding system (literature review **subchapter 1.5.2**). Data on group stability, group size and feeding system were also collected in our study (**chapter 5**). In 14 out of 15 herds, sows were housed in static groups. The lower odds for lameness development with increasing floor space allowance and in general the final logistic regression model as found in **chapter 5**, might therefore particularly apply to sows housed in static groups. Group size was weakly correlated ($\rho = -0.188$) with the floor space per sow and was not retained in the final multivariable model. This may suggest that the negative association found between lameness development and floor space allowance probably was independent of group size in these herds. Feeding system was not retained in the final model. However, the number of herds in many categories of feeding system might have been too low to study the effect of this variable. Although a significant negative association between floor space allowance and lameness was shown in **chapter 5**, the optimal space allowance to prevent lameness development could not be defined based on these results alone and requires further research.

Results of this thesis also demonstrated that **dirty sows** (> 10% of the body covered with manure) have a higher odds for lameness development compared to clean sows (< 10 % of the body soiled) (**chapter 5**). Based on the strong association between both variables, it was suggested that the level of dirt on a sow's body could be used as a proxy indicator for lameness in early gestation and sow welfare in general. Sow dirtiness as a measure of welfare

has previously been suggested by Geverink et al. (2009). To test how useful sow dirtiness might be as an indicator of lameness, sensitivity (i.e. the percentage of true lame sows that are correctly defined as lame based on the sow dirtiness score) and specificity (i.e. the percentage of true non-lame sows that are correctly defined as non-lame based on the sow dirtiness score) were calculated using the data collected in **chapter 5**. A sensitivity and specificity of 43% and 70%, respectively, were found. The low sensitivity implies a high number of false negatives indicating, albeit the strong association, dirt on a sow's body might not be a good indicator of lameness. What caused the strong association between dirtiness and lameness remains unclear. Floor dirtiness was not retained in the model which may indicate that soiling of the floor probably did not cause higher odds for lameness. The lack of significant interactions in this thesis (**chapter 5**) with both floor space allowance per sow and herd size suggests that the association between lameness and dirtiness was not influenced by these variables. Aggression could have been a conceivable link between sow dirtiness and lameness as aggressive encounters, measured in terms of skin lesions, have significantly been correlated with sow dirtiness (Geverink et al., 2009) and have frequently been suggested to result in lameness (Gjein and Larssen, 1995; Anil et al., 2005). However, in **chapter 5** of this thesis, it was shown that aggression between sows was not a risk factor for lameness within the first days of group-housing. The lack of a significant correlation between body lesion score and movement disorders in group-housed sows was reported before (Andersen and Bøe, 1999). Yet, when using lesion score as an indicator of post-mixing aggression, only injurious aggressiveness is quantified. Aggression that does not lead to physical injuries like pushing, is neglected. Such encounters might however also contribute to movement disorders. Other factors that may affect the development of skin lesions in sows after grouping should be examined.

Finally, a logarithmic decrease in the percentage of sows that developed lameness was shown when the **herd size increased** from 144 sows to 750 sows (**chapter 5**). Improved management with increasing herd size may have influenced this association. Nevertheless, it should be noted that also on small herds, low incidences of lameness could be found within the first days of group-housing. On some herds, measures were taken to minimize post-grouping aggression (*e.g.* locked up the first days of group-housing in case of free access stall or use of odorous sprays when moved to group-housing). These management practices were not taken into account in this thesis. Therefore, future field research should elucidate the effect of herd size including the role of management practices such as rearing management and measures to reduce post-mixing aggression.

At last, three general points of discussion need to be mentioned. In both **chapter 4** and **5**, animals were observed in their natural setting what results in a higher external validity compared to experimental study designs. As with any observational study however, causality cannot be claimed. Associations between lameness on the one hand and reproductive performance and influential factors on the other hand have been revealed but further research is necessary to identify the specific causes. In both studies (**chapter 4 and 5**) locomotion has been visually assessed using a three-point numerical scale. Nonetheless, due to the low number of sows within each category of lameness, only a distinction was made between lame and non-lame sows when performing statistical analysis. It can however be assumed that the effect on reproductive performance might differ depending on the severity of lameness. Moreover, lameness is a general clinical sign reflecting the presence of locomotor disorders. Nor in the study on the implications of lameness neither in the study on risk factors for lameness development, the underlying cause of lameness was diagnosed. Yet, it could be assumed that the effect on reproduction may be different depending on the cause of lameness. Similarly, the factors that influence the development of lameness might also differ according to the diagnosis. In future lameness research, it would therefore be recommended to make a distinction according to both the degree of lameness and the underlying causes.

6.4 PERSPECTIVES FOR FUTURE RESEARCH

6.4.1 TOWARDS EARLY LAMENESS DETECTION IN SOWS

Results in this thesis have demonstrated that the developed device, SowSIS, is able to distinguish visually non-lame from lame sows. Nonetheless, besides the improvements described in **subchapter 6.2**, further studies are necessary before the ultimate goal, detection of incipient sow lameness at an earlier stage than visual assessment can be reached (Fig. 2).

- The results of the proof-of-concept study (**subchapter 3.3.4**) need to be confirmed in a large-scale validation study also including visual stance variables.
- To be able to identify lame sows by the use of SowSIS, a lameness detection algorithm needs to be established based on the force and visual stance variables. To classify sows into non-lame and lame groups, probabilistic neural network models (PNN model) (Pastell and Kujala, 2007) or classification trees (Abell et al., 2013) can be used. Both PNN models and classification tree analysis include training using a teaching data set followed by validation using data independent of the teaching data set. However, the use of both PNN models and classification trees can be restricted to the specific characteristics of the herds used to build the model. Consequently, PNN models and classification trees should be trained with data from numerous sows and many different herds. Moreover, probabilistic neural network models and classification trees are general classification methods that are applied to all sows. Yet, sows are individuals that can differ in many aspects (*e.g.* parity, conformation, restlessness) and therefore they cannot always be judged with the same criteria. Non-lame sows were found to have a moderate to high between-animal variance in both force and visual stance variables (**chapter 3**) which can make detection of mild lameness cases challenging. Hence, individual statistical models for each sow may yield better sensitivity than general models. The concept of Synergistic Control, using control charts, would therefore be more suitable (Mertens et al., 2009). These statistical based control charts may identify lameness by detecting and visualizing critical deviations from target values in data series (*i.e.* repeated measurements of stance variables over time). The target values and critical deviations are calculated from the sow's own historical data so that each animal has an individual chart. The concept of Synergistic Control for lameness detection however requires that each sow is measured on a frequent basis, preferably at least once a day. Installing the four load cells and a guppy camera into an electronic feeding station offers a possibility for automatic and repeated

measurements of the force and visual stance variables. The identification of the sow in the electronic feeding station can be automatically linked to the SowSIS measurements.

- Once the detection algorithm is developed, it has to be validated. To evaluate the accuracy of lameness detection algorithms, the sensitivity and specificity (measures of accuracy) as well as predictive values (measure of usefulness in a population) should be determined (Dohoo et al., 2009b). The classical accuracy paradigm is based on studies that compare the results of the detection method under evaluation with results of the gold standard, *i.e.* the reference standard that is the best available method to determine the presence or absence of the condition of interest (Rutjes et al., 2007). Yet, there is no accepted gold standard to detect lameness in sows. The use of a detection method with already known sensitivity and specificity could be a possible solution (Dohoo et al., 2009b). Anil et al. (2008) reported the sensitivity and specificity of a visual lameness scoring system (Feet First® Team, 2009) by which the level of lameness in group-housed sows was scored on a scale of zero to three. However, visual lameness scoring systems are observer dependent and therefore, sensitivity and specificity may change when used by other observers. When there is neither a gold standard, nor a detection method with known sensitivity and specificity, latent class analyses have been proposed to estimate sensitivity and specificity of detection methods without any assumption about the true disease status of each animal (Uebersax and Grove, 1990; Goetghebeur et al., 2000; Anil et al., 2008). An alternative approach to assess the accuracy of SowSIS based lameness detection methods might be the induction of lameness in sound sows. A successful lameness induction method, using amphotericin B injected in the distal interphalangeal joint of both claws, has been demonstrated to induce a predictable acute lameness in sows that resolved spontaneously without long-term residual effects (Karriker et al., 2013). The ability to evaluate the same individual, both as lame and non-lame, has the advantage of controlling for animal-related variation (*e.g.* parity, stage of gestation, hoof structure). As amphotericin B induces primarily acute lameness, this technique will probably be less suitable to evaluate chronic and slight lameness. In analogy with the induction of lameness in sound sows, analgesics or local anaesthetics might be used in lame sows. However, the use of analgesics may be less appropriate for the validation of the lameness detection method. Analgesics have been demonstrated to improve gait and posture abnormalities in cattle (Flower et al., 2008) and broilers (Danbury et al., 2000) but some degree of lameness often persisted, suggesting that the analgesics tested were not entirely effective or part of the deviation from normal gait is caused by factors other than pain.

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- To further improve sensitivity and specificity of the lameness detection method, knowledge on how force and visual stance variables are affected by factors other than lameness should be investigated. In future research, the impact of sow head movements and people passing during measurements, on force and visual stance variables should be quantified. Head movements may be observed and recorded using video cameras. The human-animal relationship can be evaluated using the Welfare Quality® Protocol (Welfare Quality®, 2009).
 - Finally, it must be evaluated whether SowSIS is able to detect incipient lameness at an earlier stage than visual assessment. Therefore lameness in sows should be monitored using both the developed device and a visual scoring system. The six-point numerical rating scale developed by Main et al. (2000) may be advised as this scoring system has been reported to be repeatable with trained observers. For people unfamiliar with scoring of lame sows, also the tagged visual analogue scale (tVAS) developed by Nalon et al. (2013) can be used.

Once SowSIS is fully operational, it is not intended to be a lameness detection tool for lameness research purposes only. The increasing size of pig herds, housing sows in large groups and the limited amount of time available to observe sows are factors that contribute to the fact that pig producers can benefit from implementation of the device on-farm. For commercial use, automation of lameness detection by use of SowSIS is a prerequisite. Installing the four load cells and a guppy camera into an electronic feeding station offers a possibility for automatic and repeated measurements. Further research should investigate possibilities to implement SowSIS in other group-housing systems. Implementation of the device at the drinking nipples might be a possible location for measurements of sows housed in free access stalls. The concept of forced sow traffic could be another alternative although this will require more space and thus larger pens. Furthermore, a detailed economic analysis should be performed with the cost of implementing SowSIS on-farm on the one hand and all the benefits related to lameness control and prevention on the other hand.

SowSIS in its present form is developed to measure gilts from six months of age as well as older sows. Yet, in the future the device could also be adapted to monitor lameness in fattening pigs. Lameness has been reported to be an important disease condition in fattening pigs with a negative impact on the pig's welfare and a negative influence on the farm profitability (Jensen et al., 2007; Jensen et al., 2012). Hence, producers of fattening pigs can

benefit from early lameness detection by a modified version of SowSIS that can adapt to the size of the pigs. To adjust the feed supply during the fattening round, automatic pig scales measuring the weight of each pig daily, are available for on-farm use. Implementation of our system into an automatic pig scale in combination with an individual pig identification system may be an opportunity for the use of SowSIS in fattening pigs. In the first place, this modified device can be used to perform research on the prevalence of lameness in fattening pigs and to define influential factors that are manageable and that can be implemented in preventive strategies. Studies should elucidate the benefits of early lameness detection in fattening pigs with regard to weight gain and feed conversion. Furthermore, economic analyses should reveal whether the benefits related to early detection of lameness outweigh the costs related to the implementation of the device. As the cost per pig will decrease as the number of pigs per device increases, the implementation of the device will likely be restricted to large herds housing large numbers of fattening pigs.

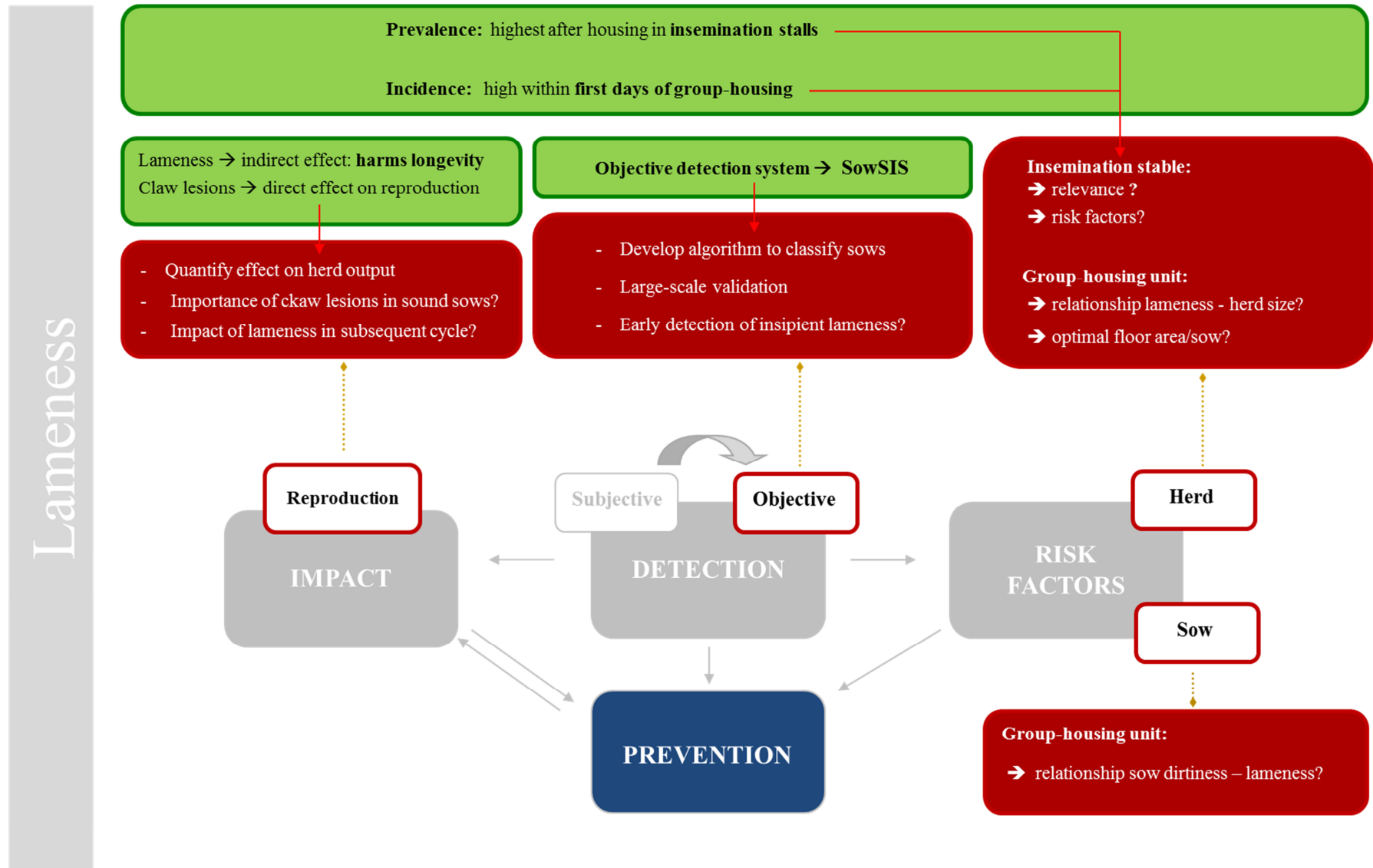


Fig. 2. Schematic representation of implications for future research

6.4.2 REVEALING ECONOMIC IMPLICATIONS AND RISK FACTORS

The results found in this thesis do not yet allow a detailed estimation of the financial loss in euro terms, neither are they directly applicable as preventive measures. They provide nevertheless valuable insights that may contribute to a better understanding of lameness and suggest direction of further research (Fig. 2).

Claw lesions have been demonstrated to be significantly associated with sow farrowing performance whereas no clear direct association between lameness and farrowing performance could be found. Therefore, the different leg and foot disorders present in group-housed sows, their relation with sow lameness as well as their impact on sow reproductive performance need to be investigated. Results of these studies should elucidate whether and to what extent leg and foot disorders may affect reproductive performance of sows without lameness being present. Furthermore, it has to be investigated whether lameness during gestation or lactation might affect sows' reproductive performance in a subsequent cycle and whether the effect of lameness differs depending on the severity and the underlying causes. Also a more detailed study is necessary to quantify the effect of lameness on the herd output, measured in pigs per sow per year, as a result of the impact on sow longevity. Finally, an economic analysis, based on the results of the previous studies, will have to be performed to estimate the financial loss, in euro, related to lameness.

Although awareness of the economic implications may promote action against lameness, economic arguments are not the only and not necessarily the main motivators to encourage farmers to change management practices (Valeeva et al., 2007; Greiner et al., 2009; Leach et al., 2010b). Pride in a healthy herd and welfare concerns have also been reported to be strong drivers to prevent lameness in dairy cattle (Leach et al., 2010b). In addition, restricted time and labour, a high tolerance and low order of priority to lameness have been identified as barriers to dairy farmers (Leach et al., 2010a). Likely, knowledge on the economic implications alone will neither be sufficient to encourage pig producers to take action against sow lameness. Therefore, questionnaires that yield information on pig producers' perception of the lameness problem as well as the barriers and motivators to tackle sow lameness and to implement control measures (*e.g.* SowSIS) need to be carried out. The revealed information may help to improve prevention of sow lameness and hence to promote sow welfare.

Within the first days of group-housing, the lameness incidence was found to be relatively high. The long-term effect of this high incidence has to be revealed, *i.e.* do sows, that develop lameness within the first days of group-housing, heal quickly or do they remain lame for a longer period of time. Although in this thesis both the prevalence at the end (**chapter 4**) and the incidence at the beginning of group-housing (**chapter 5**) have been determined, they have never been investigated within the same study. By means of a longitudinal study, lameness development could be followed up throughout the period of group-housing. Additionally, sows that develop lameness may be diagnosed in order to determine the main underlying causes. Knowledge on the underlying cause and whether sows develop acute or chronic lameness may help to improve notion of welfare implications and to establish control measures.

In this thesis, insights have been gained on the risk factors for lameness development within the first days of group-housing. However, further research is necessary before the practically useful control and preventive strategies can be established. The importance of the insemination stable with respect to lameness development needs to be clarified and influential factors that are manageable have to be defined. Risk factor analysis does not only have to focus on the period in the insemination stalls but should also include the period before. Further research is necessary to determine the optimal space allowance to prevent sow lameness post-grouping and during gestation in general. When studying space requirements, also group size, group stability, pen design and feeding system must be taken into account. Results of these studies should reveal whether the recommendations of the EU suffice to prevent sow lameness. Future research also needs to elucidate the relationship between lameness development and herd size. The influential factors have to be defined in order to find measures to minimize sow lameness. Particularly the impact of management practices such as measures to reduce post-mixing aggression and rearing management should be included. Aggressive encounters and floor characteristics did not seem to play a role in lameness development short after introduction in group-housing. Yet, the importance of aggression and floor characteristics on lameness development in the long-term still has to be revealed. When using skin lesions as a measure of aggressive behaviour, one must bear in mind only injurious encounters are quantified while encounters such as pushing are neglected. Behavioural observations may be helpful in this respect. Finally, in future research, risk factor analysis may also focus on other stages in the reproductive cycle and influential factors might

be identified for lameness development in general as well as separately for each of the underlying causes of lameness.

In both observational studies of this thesis (**chapter 4 and 5**) lameness was detected using visual assessment. Once SowSIS is able to detect lame sows with a sufficient sensitivity, specificity and precision at an earlier stage than visual assessment, the detection method can be used to further evaluate the economic implications and risk factors for lameness. For example, the effect of limb conformation traits, measured by SowSIS, on the risk for lameness development could be investigated. It has been shown that gilts with an improper leg conformation have a higher risk for lameness development than gilts with a good to excellent conformation (Diaz et al., 2013). Furthermore, leg conformation plays a key role in sow longevity, incurring substantial repercussions for the economic performance of the herd and well-being of sows (López-Serrano et al., 2000; Tiranti and Morrison, 2006; Tarrés et al., 2006; de Sevilla et al., 2008). An accurate culling of gilts with poor leg conformation before first mating will improve sow longevity. Conformation traits are low to moderately heritable and could be taken into account when selecting replacement gilts (Tarrés et al., 2006; de Sevilla et al., 2008). Evaluation of feet and leg structure soundness is mainly performed using visual scoring systems (Van Steenbergen, 1989; Serenius et al., 2001; Tiranti and Morrison, 2006; Guo et al., 2009). Given the subjectivity and risk for observer error of visual scoring systems, more objective tools are needed to evaluate leg conformation traits. Accurate and precise conformation scoring may contribute to a more correct selection of gilts on leg conformation traits and may improve longevity and - hence - welfare of sows. Objective and precise information on the sow's standing posture can be derived from the visual stance variables acquired with SowSIS. Longitudinal studies, including follow-up of leg conformation during several reproductive cycles and commencing at the moment of gilt selection, could reveal which values for each of the three visual stance variables, are associated with a higher risk for lameness development and for premature culling due to lameness. Cut-off values to enable classification of a sow's limb conformation as being acceptable or unacceptable, will have to be defined. Once these standards are known, SowSIS may be used by breeding companies to assess limb conformation of future breeding stock.

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General conclusions and implications

This thesis aimed to enhance control and prevention of lameness development in group-housed sows by refining detection, elucidating implications for reproductive performance and identifying risk factors.

Based on the results presented in this thesis, the following conclusions can be put forward:

1. A system, based on force and visual stance variables derived from balance analysis and image processing respectively, was developed: SowSIS. The developed system, that detects lameness in sows while standing, proved to be highly accurate ($R^2 \approx 1$) for measuring weight and permitted registration of both force and visual stance variables with a sufficient level of precision (Coefficient of variation $\leq 15\%$). Non-lame sows can be discriminated from unilateral lame sows based on the force stance variables acquired with SowSIS. Whilst the system has promise, the further development of algorithms for fully automated lameness detection using this equipment remains to be carried out.
2. Lameness affects the overall herd performance mainly through a detrimental effect on sow longevity. By contrast, the presence of claw lesions might directly affect the presence of stillborn piglets and mummified foetuses. Yet, further research is warranted to confirm the relationship between claw lesions and sow reproduction, and to investigate possible confounding factors.
3. The prevalence of sow lameness differs between herds and varies throughout the reproductive cycle suggesting that lameness should be assessed at different times throughout a cycle to determine the severity of a lameness problem in a herd.
4. The odds for lameness development shortly after introduction in group-housing decreases with increasing floor space allocated per sow, decreasing dirtiness of the sow's skin and increasing herd size. Despite the strong association, a low sensitivity was found for sow dirtiness as an indicator of lameness within the first days of group-housing. In further research the optimum floor space allowance to prevent lameness development should be determined and the factors that influence the association between herd size and lameness development has to be defined.

Curriculum Vitae

Liesbet Pluym werd geboren op 30 mei 1985 te Zottegem. Na haar middelbare studies (Latijn-Wetenschappen) aan het O.L.V. van Deinsbeke College te Zottegem, startte ze in 2003 met de studie Diergeneeskunde aan de Universiteit Gent. In 2009 behaalde ze met grote onderscheiding het diploma van Dierenarts – Optie Varken, Pluimvee en Konijn. Voor haar afstudeerwerk ‘Voorkomen en belang van poot- en klauwproblemen bij zeugen in twee types groepshuisvesting’ (promotor: Prof. dr. D. Maes) ontving ze de prijs voor beste scriptie m.b.t. varkens evenals de ‘Boerenbondpersprijs 2009’.

Geboeid door beenwerkproblemen bij zeugen engageerde ze zich samen met haar promotoren in de zomer van 2009 voor het uitschrijven en indienen van een IWT project rond kreupelheid bij zeugen. Na een succesvolle verdediging van het project eind 2009, vatte ze op 1 januari 2010 haar doctoraatsonderzoek aan op de Vakgroep Voortplanting Verloskunde en Bedrijfs-diergeneeskunde van de UGent. Dit vier jaar durende project werd gefinancierd door het Agentschap voor Innovatie door Wetenschap en Technologie (IWT) en werd uitgevoerd in nauwe samenwerking met de Eenheid Technologie en Voeding van het Instituut voor Landbouw- en Visserij Onderzoek (ILVO). Naast haar onderzoek was ze ook betrokken bij de bedrijfsbegeleiding binnen de eenheid Varkensgezondheidszorg.

Liesbet Pluym is auteur of mede-auteur van meerdere wetenschappelijke publicaties en lichtte haar onderzoeksresultaten toe op verschillende nationale en internationale congressen.

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toestel is gebouwd geraakt, het heeft de eerste 250 zeugen overleefd, er zit potentieel in dat er door een volgende doctoraatstudent hopelijk helemaal zal uitgehaald worden en er is, weliswaar na een korte veldslag, ook een artikel over verschenen in de wetenschappelijke literatuur. Intussen ben je zelf ook aan je doctoraat aan het schrijven. Ik wens je het allerbeste toe en laat maar weten wanneer de verdediging is!

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