ARE INFRARED THERMOGRAPHY, AUTOMATED FEEDING SYSTEMS, AND HEART RATE VARIABILITY MEASURES CAPABLE OF CHARACTERIZING GROUP-HOUSED SOW SOCIAL HIERARCHIES?

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

Dominique Marie Sommer

In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Department:
Animal Sciences

June 2022

Fargo, North Dakota

North Dakota State University
Graduate School

Title

Are Infrared Thermography, Automated Feeding Systems, and Heart Rate Variability Measures Capable of Characterizing Group Housed Sow Social Hierarchies?

By

Dominique Marie Sommer

The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

SUPERVISORY COMMITTEE:

Christopher J. Byrd
Co-Chair

Xin Sun
Co-Chair

Giancarlo Lopez-Martinez

Approved:

August 3, 2022
Date

Guillermo Scaglia
Department Chair

ABSTRACT

Group gestation housing is becoming standard practice in commercial swine production. Although group housing promotes behavioral variability within the breeding herd, it can cause several management challenges for producers due to the establishment of the social hierarchy. Poor performance and welfare in group housed breeding stock can be attributed to the repercussions of aggression performed between dyads. The ability to quickly identify sows in the social hierarchy could be beneficial to producers for enforcing preventative actions. Precision livestock farming tools have proven to aid animal caretakers in monitoring animal health and welfare in livestock industries.

The objective of this thesis was to investigate the use of infrared thermography, feeding activity obtained from an automated radiofrequency identification feeding system, and heat rate variability indices for detecting the social hierarchy within groups of gestating sows. Additionally, the relationship between observed social hierarchy, body condition scores, backfat, and reproductive performance was also explored.

ACKNOWLEDGMENTS

Dr. Chris Byrd, I can’t express all my gratitude for your guidance, advice, and patience throughout my time as your graduate student. A simple ‘thank you’ will never be enough for the lessons you’ve taught me. Dr. Giancarlo Lopez-Martinez and Dr. Rex Sun, thank you for your constant support, help, and encouragement throughout this project. Dr. Jennifer M. Young, you are absolutely wonderful and none of this would have been possible without you, thank you. Dr. Lauren L Hulsman-Hanna and Dr. Kendall Swanson, I have loved learning from you both, not only about research but academia and life.

Gregg Bauman, your encouragement and support has gotten me through my program here in North Dakota. I am forever grateful for you.

Natalie Acosta-Castellanos, there are not enough words in the English, or Spanish, language to tell you how appreciative I am to have you as a best friend and mentor. You have rescued me more times than I can count, and I will always find a way to visit you. Maverick Guenther, all I can say is that you saved me when you started your program. A big thank you to my fellow graduate students for the fun memories at NDSU, as my time in the Cubes is an experience I will never forget.

My journey into agriculture started in high school, but I would never be where I am today without the people who sparked my passion for livestock production. BJ Macfarlane, I am forever grateful for the skills you’ve taught me and the opportunities you helped me recognize in the world around me. You believed in me when I didn’t believe in myself, and the remainder of my life will be dedicated to helping young adults in agriculture like you did for me. Melissa, Addi, Ellis, and Maddox, you all are so inspiring to me and my time with you were some of the happiest of my life. Trena Kimler-Richards, you saw something in me and pushed me until I saw

it myself. Thank you for always keeping me accountable and never accepting anything but 110%.

Although I never imagined coming to the Midwest, my professors at Fresno State are truly the ones who encouraged me to take this opportunity. Dr. Fabio Iared, you were the most caring professor who I truly enjoyed learning from. Thank you for reminding me that asking questions in class is more beneficial than struggling behind closed doors. My time in meat science was short, but I am the luckiest to have learned what I did from Dr. John Henson. Every course I took was more interesting and challenging than the last. Thank you for being the professor you are who truly believes in a good work ethic. When I started at Fresno State, I was warned to avoid classes with Dr. Scott Williamson because he was tough teacher, and his classes were difficult. I took every class I could with Doc and loved each one. Thank you, Doc, for expecting a lot from me and challenging me. You are the greatest professor I ever could have asked for, and I will always "make the best better".

Thank you to my family for your support and encouragement while I have been away from home. It has been a difficult experience in graduate school, but each time I called and wanted to come home, you reminded me why I started. To Alex, thank you for sticking with me through this journey.

Lastly, the biggest thank you to the sweetest sows I could have ever asked to work with. I love each and every one of you and I will miss our mornings together dearly.

DEDICATION

I dedicate this thesis, in its entirety, to my dad,

Robert J. Sommer.

I am lucky enough to have the world’s best dad and most caring and empathetic best friend.

Dad,

Everything I am, is because of you.

I will never be able to repay you, but I owe you everything.

“Head up, charge forward”

Love,

Nique

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BCS	Body condition score
BCS3	Body condition score, three-point scale
BCS6	Body condition score, six-point scale
BF	Backfat depth (mm)
DI	Dominance index
ESF	Electronic sow feeding system
HR	Heart rate
HRV	Heart rate variability
IRT	Infrared thermography
MaxT	Maximum temperature of thermal image region of interest
MeanT	Mean temperature of thermal image region of interest
MinT	Minimum temperature of thermal image region of interest
PLF	Precision livestock farming
RFID	Radio frequency identification
RMSSD	Root mean square of successive differences (ms)
ROI	Region of interest
RQ	Rank quartile
RR	Mean RR interval (ms)
SDNN	Standard deviation of all RR intervals (ms)

1. LITERATURE REVIEW

1.1. Introduction

Animal welfare in commercial livestock production is an essential component of producing sustainable food animal products. In recent decades, consumer concerns regarding livestock welfare, as well as changing preferences, have led to changes in the way swine are handled and housed in commercial production systems and due to this increasing interest, food corporations have begun to require changes to traditional production practices. Additionally, production practices have changed in response to legislation, niche markets, certification programs, and auditing programs that specifically focus on animal welfare (Mench, 2008).

One major example of those changes deals with sow housing during the gestation period. Traditional gestation housing utilizes individual stalls to house sows independently from other gestating sows within the breeding herd. Individual stall housing systems offer a way to house breeding females in a manner that conserves space (Hemsworth, 2018b) and provides individual management of individuals regarding breeding and insemination, health, and feeding (Harris et al., 2006; Koketsu and Iida, 2017). However, there are concerns that arise from this restrictive housing system; most notably, the limitations individual stalls place on sow movement (Childers et al., 2004). As a result, alternative forms of housing, such as group gestation housing, have become more prevalent in commercial swine production.

Group gestation housing, or “group housing”, allows individual sows the ability to move freely within a large pen and interact with other sows, which is restricted in individual stall housing (Barnett et al., 2001; Harris et al., 2006). However, despite these benefits, group gestation housing also leads to several challenges that may negatively impact a sow’s welfare. For example, skin lesions and lameness, which can be due to aggression from social hierarchy formation, poor body condition, and possibly impacted reproductive performance (Rhodes et al., 2005). Therefore, strategies for monitoring individual sows are needed to effectively improve sow welfare within group gestation pens.

Precision livestock farming (PLF) technologies provide a potentially useful method for monitoring sow welfare through continuous, real-time monitoring of individual animal health, welfare, reproduction, and productivity (Berckmans, 2014). Precision technologies are capable of providing useful knowledge about the herd and may help caretakers identify animals in need (Berckmans, 2017). For example, infrared thermal imaging has proven to be a useful non-contact precision tool in the early detection and identification of immune compromised swine (Cook et al., 2015), cattle (Rainwater-Lovett et al., 2009), and sheep (Perez de Diego et al., 2013), as well as aiding in the detection of stress (Nääs et al., 2014). Additionally, technologies like electronic sow feeding (ESF) systems that are commonly employed in group gestation systems utilize radio frequency identification (RFID) technology to identify individual animals and document important changes in various feeding characteristics (Vargovic et al., 2021). These technologies, among others, could prove to be beneficial for improving the welfare of group-housed sows, particularly as a method for characterizing the social hierarchy within the group and identifying sows at risk of poor welfare outcomes related to hierarchy formation.

1.2. Conceptualizing Sow Welfare

Animal welfare is defined as an animal's state in regards to its attempt to cope with its environment (Broom, 1986). Traditionally, the concept of animal welfare is broken down into three domains: biological functioning, natural living, and affective states (Fraser et al., 1997; Marchant-Forde, 2015; but see Mellor, 2017 for a recent 5-domain conceptualization). Biological functioning refers to growth, health, and productivity of an animal (Fraser, 2003) and is likely the most commonly evaluated domain by producers and veterinarians. Natural living emphasizes that the welfare of an animal is improved or enhanced if that animal is given the ability to express their natural behaviors (*e.g.*, rooting in swine, grazing in cattle, dust bathing in chickens; Hemsworth et al., 2015). Finally, affective state concerns the mental wellbeing of the animal, including the lack of suffering and fear, and the experience of positive emotions, such as playfulness and satiety (Mendl et al., 2010). These three domains overlap and affect one another since animal coping strategies often require behavioral, physiological, and psychological responses to effectively cope with their environment (Broom, 2011).

1.2.1 Biological Function

An animal's biological function (*i.e.* health, reproduction, growth) is negatively affected by exposure to various stressors (Broom, 1988; Broom, 1991), which is ultimately reflected in that animal's welfare state (Broom, 1991; Mendl et al., 1992; Fraser, 2008; Hemsworth et al., 2015). However, production outcomes and measures indicative of biological function are not necessarily sole indicators of an animal's welfare state (McGlone, 2001; Dawkins, 2006; Mellor and Webster, 2014). Regardless, the biological functioning of an animal has traditionally been the main welfare concern for veterinarians and producers, and for some individuals, is the sole indicator of identifying an animal's welfare state. For example, McGlone (1993) stated that, "an animal is in a poor state of welfare only when physiological systems are disturbed to the point that survival or reproduction are impaired." This perspective is common, since an animal's ability to grow or reproduce is often thought to rely on good health. Therefore, measures indicative of good health, growth, and productivity are often utilized as indicators of an animal's welfare state.

Animal caretakers frequently utilize various indicators of biological functioning to identify compromises to an animal’s welfare. For instance, weight gain for animals entering the food chain (Hemsworth et al., 1987) or reproductive success in breeding stock (Fraser, 2003; Ritter et al., 2019) are relatively simple measures to observe if observations are performed routinely and correctly. If an animal is not gaining weight, it may be due to an inability to eat, injury, or illness. Other observable indicators of biological function include skin lesions and lameness in swine and cattle that can lead to discomfort, pain, and infection. The effects of these injuries can be long-lasting if not addressed and can further negatively affect an animal’s welfare and production output (Winckler and Willen, 2001; Nalon et al., 2013).

Physiological stress experienced as a result of an environmental stressor affects biological functioning because it alters physiological homeostasis, or equilibrium (NseaAbasi et al., 2013). When homeostasis is challenged, a cascade of physiological processes are initiated in response to maintain homeostasis (Sutanto and de Kloet, 1994). These processes often involve changes to physiological indicators like cortisol, the cardiovascular response, and blood flow (Buchanan et al., 1999). Unfortunately, measures like plasma cortisol are easily affected by conditions outside of the user’s control (Broom, 2017) and they are impractical for producer use.

1.2.2. Natural Living

Natural behavior, defined as behavior that animals have a tendency to exhibit under natural conditions (Bracke and Hopster, 2006), is considered to be an essential component for evaluating an animal’s welfare. Various perspectives on the expression of natural behaviors exist, with some individuals believing it is essential for animals to perform all behaviors within their repertoire because they all serve a function (Kiley-Worthington, 1989). Additionally, not only do these behaviors serve a function, but their performance may also be pleasurable for the animal and beneficial for an animal's welfare (Bracke and Hopster, 2006; Hemsworth et al., 2015; Browning, 2020). Others believe domesticated species have adapted to conditions which have been imposed upon them. Therefore, some innate behaviors that were once essential for survival may no longer serve a function (Fraser et al., 1997; Green and Mellor, 2011). However, regardless of an individual's belief regarding natural living, the ability of an animal to perform motivated behaviors, whether innate or developed through adaptation, is critical for living within an environment (Fraser et al., 1997) and therefore impacts welfare.

Certain behaviors can provide an indication of an animal's welfare state. The ability to perform highly motivated behaviors such as exploration in group-housed sows (Verdon et al., 2015), rooting and play behavior in swine (Lay Jr. et al., 2000), and grazing in dairy cattle (Beaver et al., 2020) may indicate that these animals have better welfare than those who do not perform those same behaviors. Other behaviors, such as stereotypical behaviors, which are "repetitive, invariant behavior patterns with no obvious goal or function," can indicate that an animal's welfare is poor, as these behaviors often result from the inability to perform motivated or natural behaviors entirely or to satisfaction (Forrester, 1980; Mason, 1991; Mellor, 2015). For instance, sows have been observed to perform bar biting when housed in individual stalls and tethered housing (Rushen, 1984; Vieuille-Thomas et al., 1995), which can be attributed to limited stimuli offered by their environment (Hemsworth, 2018b). Therefore, when evaluating animal welfare, it is critical to consider not only particular behaviors being performed by the animal, but also the possible reason for the behavioral motivation.

1.2.3. Affective State

Affective states are associated with animal sentience, or the nature of emotions that accompany pleasure and suffering (Webster, 2001). Scientists have continued to emphasize the importance of understanding animal sentience in order to evaluate animal welfare (Rushen, 2003; Mellor and Webster, 2014), with some suggesting that animal welfare relies solely on the cognitive needs of an animal since the animal's health and productivity will be impaired if their psychological needs are not met (Duncan and Petherick, 1991). However, scientists who prioritize the importance of affective states recognize that affective states are closely tied to biological functioning and behavior. Therefore, measures related to biological functioning and behavior are required for understanding affective states in animals (Broom, 1988; Fraser, 2003; Hemsworth et al., 2015). Other scientists believe that inference to affective states from biological or behavioral measures is inherently flawed (Duncan and Dawkins, 1983).

Our ability to evaluate affective states in animals, especially positive emotional states, is expanding. Initially, the affective state-based concept of animal welfare focused on the freedom from suffering (*e.g.* experiencing pain for extended amounts of time), fear, hunger, and other negative emotions (Fraser et al., 1997; Marchant-Forde, 2015). However, the concept has grown to also include the experience of positive affective states such as pleasure, happiness, and comfort (Broom, 2010; Hemsworth et al., 2015; Marchant-Forde, 2015; Mellor and Beausoleil, 2015). To investigate affective states in farm animals, researchers have utilized behaviors performed by an animal in response to a stimulus to indicate positive and/or negative emotions (Désiré et al., 2002; Murphy et al., 2014). For instance, play behavior in mammals is easily detectable and is commonly linked to positive emotions (Held and Špinka, 2011; Horback, 2014). In addition to play behavior, the behavioral response to rewarding and undesirable events can be used as a useful indicator of affective states in swine (Reimert et al., 2013; Reimert et al., 2015). Preference tests have also been used to evaluate subjective or affective states to aid in psychological welfare assessment (Scollo et al., 2014; Horback and Parsons, 2019).

In addition to behavior, the physiological response to positive and negative stimuli can be used as an indicator of affective state. For example, research investigating the effect of music on rodent welfare within a laboratory setting reported lower blood pressure and increased dopamine levels in response to treatment, inferring that the cognitive state of animals exposed to certain types of music can be improved (Alworth and Buerkle, 2013). This demonstrates an animal's ability to experience different subjective emotional states when encountering novel stimuli.

Overall, these three domains (*i.e.* biological functioning, natural living, and affective states) are commonly identified by scientists as valid components of an animal's welfare (Fraser, 2003). However, differences in scientists' personal values can affect which domains they consider to be essential (Fraser, 2003). Regardless, an effective animal welfare assessment likely includes aspects of all three domains since they often influence one another.

1.3. Traditional Sow Gestation Housing

Given the potential impact of environment on an animal's overall welfare, it is essential to understand the effects of commercial sow housing systems on sow welfare. With a continued trend towards intensification of pork production in the United States, traditional individual stall gestation housing systems offer a way to house and manage multiple breeding females in a manner that conserves space within a production facility (Hemsworth, 2018a). These individual stalls vary in size (*i.e.,* lengths ranging from 1.98 - 2.10 m and widths between 0.61 - 0.76 m; HSVMA, 2013), and are typically positioned directly adjacent to additional stalls housing the remaining sows within the gestation herd. In many cases, this type of system improves the management of individual animals; particularly regarding breeding, health, feeding, and farrowing compared to other housing systems (Karlen et al., 2007; Koketsu and Iida, 2017). For example, this housing type offers sows access to their entire feeding ration without having to compete with other conspecifics. Some studies have also reported that sows housed in individual stalls exhibit fewer signs of lameness (Anil et al., 2005; Harris et al., 2006; Jang et al., 2015) and fewer culling instances due to lameness (Chapinal et al., 2010; Koketsu and Iida, 2017) compared to other sow housing types.

While these systems are often beneficial for individual animal management, gestation stalls raise animal welfare concerns related to sow behavior (Hemsworth, 2018a). Most notably, the individual stall restricts a sow from moving freely when desired. Some sows may also be too large to avoid contact with the stall or feeder while lying down (Anil et al., 2005). As a result, skin injuries from consistent contact with the metal bars may occur. Anil et al. (2005) found that as sow weight increased, so did the rate of injury to the dorsal portion of the body, forelimbs, hind limbs, and udder in sows housed in individual stalls.

Sows housed in individual stall systems are sometimes observed displaying atypical behaviors, such as stereotypical behaviors, which are performed repetitively and serve no function to the animal (Rushen, 1984). Stereotypical behaviors can be indicative of poor welfare, as these behaviors are often performed in barren environments where the animal is restrained to some degree and is unable to escape from fearful stimuli or frustration (Mason, 1991). Studies investigating the behaviors of sows housed in individual stalls reported a greater frequency of sham chewing compared to sows housed in group pens (Karlen et al., 2007; Chapinal et al., 2010; Liu et al., 2021), which can be attributed to a lack of stimulation within the stall environment.

Although individual gestation stalls offer many benefits to the sow herd in terms of individual animal health and reproductive management, the housing systems does not provide sows the ability to move freely outside of the limits of the individual stall. Given these concerns, consumer-driven legislation (Matthews and Hemsworth, 2012), supply chain initiatives (de Jonge and van Trijp, 2013), niche markets (Honeyman et al., 2006), and certification programs have led to an increase in the use of alternative housing systems for gestating sows to allow for increased freedom of movement, social interaction, and performance of highly motivated behaviors.

1.4. Group Gestation Housing

In commercial swine production, group pen gestation housing is the most utilized alternative form of gestation housing, with approximately 33% of producers in the United States incorporating group pen gestation into their production systems (personal communication with the National Pork Producer's Council, 2022). The group pen gestation model gives sows a communal space in which they are able to move freely and interact with their pen mates (McGlone, 2013). Pen dimensions vary in size according to stocking density. No space requirements exist in the United States and research investigating the effects of group-housing space allowances on the welfare of group-housed sows is contradictory (Salak-Johnson et al., 2007; Remience et al., 2008; Li et al., 2018). However, countries outside of the United States have various minimum space requirements and recommendations that fall within 1.8 - 2.5 m^2 per sow (Council Directive 2008/120/EC. 2009; National Farm Animal Care Council, 2014). Small group gestation pens can accommodate 4-5 sows (Kemp and Soede, 2012) while large group gestation pen research has investigated stocking rates of up to 80 sows per pen (Hemsworth, 2018a). Pen designs often include a single large open communal area and a communal area with subsections created by barriers to allow opportunities for sows to escape from aggression or dominant pen mates (Hemsworth, 2018b).

1.4.1. Feeding Methods Within Group-Pen Gestation Housing

Feeding methods within group gestation pens vary according to pen design. Free access stalls provide individual feeding spaces within a communal pen. As a sow enters the free access stall, a rear gate can close and lock behind the sow while she eats. This type of feeding design gives individual sows a level of protection from conspecifics during feeding times or during aggressive interactions (Mack et al., 2014).

Floor feeding and trickle feeding provide the benefit of occupying only a fraction of the communal pen space, but these methods in group gestation housing can be challenging. Floor feeding is a competitive feeding method which dispenses feed evenly across a feeding area either by hand or automatic feeding system at a certain time each day. This type of feeding method has many challenges, as there can be no guarantee individuals are consuming their entire ration (Verdon et al., 2015). Trickle feeding is also another competitive feeding method in which an automated feed storage source drops feed into a trough or solid surface. The feeding area may have side panels to create open feeding stalls. These partial stalls offer a level of protection in terms of ration consumption (Iida et al., 2017; Koketsu and Iida, 2017). However, due to the open design of the feeding stalls, sows can be forced from their feeding space by other sows.

Lastly, an electronic sow feeding system (ESF) has the capacity to feed large groups of sows using radio-frequency identification (RFID) to identify individual sows when they enter the feeder. An advantage of the ESF is the ability to adjust feed allocation on an individual level, providing feed rations according to each sow's individual and changing needs. Specifically, when a sow enters the feeder, radio waves are emitted from the circuit transponder in an ear tag worn by the sow and are received by the RFID reader within the feeder (Benjamin and Yik, 2019). The system then registers the sow's identification, the total daily ration allotted to the sow, how much of the daily ration has been consumed, and the remaining amount in the allotment. Additionally, ESF technology has the capacity to track many other useful feeding characteristics as well (*e.g.*, missed rations and number of visits per day; Maselyne et al., 2015). Because of this technology, fewer feeders can accommodate more animals and therefore, more pen space is available for movement, behavioral expression, and lying. However, since fully enclosed ESF feeders offer individual protection during feeding bouts (*i.e.*, a swinging gate can close behind the sow after it enters the ESF), the sow can remain in the feeder for long periods of time which can prevent other sows from entering the feeder.

1.4.2. Comparison of Welfare, Productivity, and Reproductive Outcomes Between Traditional and Group-Pen Gestating Housing

Ultimately, the goal of group-gestation housing is to improve sow welfare by providing more opportunities for sows to perform highly motivated behaviors and increasing social interaction between conspecifics. Group-housed sows exhibit more exploratory behaviors compared to sows housed in individual stalls (Liu et al., 2021), and spend more time resting compared to traditionally housed sows (Chapinal et al., 2010). This could be due to the increase in pen space which may provide a favorable environment for resting compared to individually-stalled sows who may be more likely to be in a state of discomfort (Liu et al., 2021). Sows housed in gestation pens also exhibit reduced incidences of stereotypical behavior compared to sows in individual stalls (Karlen et al., 2007; Chapinal et al., 2010; Liu et al., 2021). Overall, the differences in behavioral expression and frequency that have been mentioned help indicate the group gestation housing setting allows more opportunities for different activities.

In regard to reproductive performance, Tsuma et al. (1996) found concentrations of progesterone, estradiol, and prostaglandin metabolite to be similar between group-housed (*i.e.*

groups of 3 sows) and individually housed sows. Additionally, no differences in the number of collected embryos after slaughter were found between treatments. These results are in agreement with other studies which have reported similar findings (Einarsson et al., 1996). Several studies have found that the number of piglets born and born alive per litter do not differ between group-housed and individually-stalled sows (Harris et al., 2006; Zhao et al., 2013; Jang et al., 2015). Additionally, sow farrowing rates between the two housing systems are similar, if not better in group housing. For example, Bates et al. (2003) found that sows housed in groups had a higher farrowing rate than sows housed in individual stalls (94.3% vs. 89.4%, respectively).

1.4.3. Animal Welfare Challenges Associated with Group-Pen Gestation Housing

Although group gestation housing improves sow welfare by increasing a sow's ability to perform natural behaviors and socially interact, welfare concerns not previously encountered in individual stall housing systems arise (Anil et al., 2005). For example, animal caretakers, who are responsible for observing animals and identifying challenges that occur (*e.g.* disease and injury), may have a harder time identifying each individual and reporting individualized animal concerns when sows are freely moving within a group pen. This can be more difficult in large group housing settings, where the number of animals under one's care is often extensive (Berckmans, 2017).

The most notable concern with housing sows in groups, however, is inter-sow aggression (Barnett et al., 2001). Levels of aggression are increased upon the initial mixing of sows, when new sows are introduced to previously grouped sows (Koketsu and Iida, 2017), as well as during feeding times or around ESF systems (Bench et al., 2013; Hemsworth et al., 2013; Hemsworth et al., 2016). This aggression is a result of the social (or dominance) hierarchy that is established after mixing (Arey and Edwards, 1998). The social hierarchy is created to ensure one's access to important resources (Mcglone, 1986) and is created by dominance-submissive relationships that are formed through aggressive interactions between individuals within a group (Arey and Edwards, 1998; Greenwood et al., 2014). This type of social structure among animals is common (Meese and Ewbank, 1973) and is often seen at higher intensity in confined groups of livestock due to their unnatural and confined environment. Specifically in group-housed sows, lower ranked individuals within groups have more skin lesions (Verdon et al., 2016), gain less body weight throughout gestation (Pacheco and Salak-Johnson, 2016; Norring et al., 2019), and have less access to feeding spaces (Pacheco, 2016). The impacts of these characteristics on sow welfare can be significant, as they can affect reproductive success (Greenwood et al., 2014) and therefore, economic gain for the producer.

In wild populations of swine, sows live in relatively small groups of familiar individuals where aggression typically arises when there is competition for resources (*i.e.*, food) (Rhodes et al., 2005). In commercial conditions this behavior is similar. However, the combination of limited or restricted feeding resources (Hemsworth, 2018b) and a larger number of individuals per group results in heightened competition for those resources and high levels of aggression (Anil et al., 2005). Establishing the social rank among the group consists of individuals exhibiting certain aggressive behaviors such as parallel pressing, head-to-head knocking, head to body knocking, levering, biting, and physical displacement. Individuals who are first to withdraw or retreat from a threat or an aggressive interaction are considered to be less dominant (*e.g.*, submissive) to the other individual (Jensen, 1980; Mount and Seabrook, 1993; Langbein and Puppe, 2004). The impacts of these aggressive interactions can create short term welfare concerns, such as skin lesions and other injuries. Additionally, long term effects related to aggression, like stress, lameness, and poor body condition, can possibly affect reproductive success (Munsterhjelm et al., 2008; Greenwood et al., 2014) and herd longevity.

Although aggression intensity throughout the gestation phase can decrease over time after the establishment of the social hierarchy (Arey and Edwards, 1998; McGlone, 2013), aggressive bouts can reoccur around feeding times or within feeding spaces, especially in competitive feeding systems (Spoolder et al., 2009; Hemsworth, 2018a). Previously published research has investigated methods to reduce aggression, such as boar presence (Marchant-Forde and Marchant-Forde, 2005), sedation (Maes et al., 2016), and enrichment (Greenwood et al., 2014), but these strategies only have temporary effects; the aggression between sows cannot be eliminated completely. Therefore, it could be beneficial for producers to distinguish individuals within the hierarchy in order to identify potential welfare challenges that may occur due to social aggression. However, without tools to aid the producer, determining the sow social hierarchy within groups is time consuming and impractical.

1.5. Precision Technologies as a Strategy for Monitoring Sow Welfare in Group Housing Gestation Systems

The pressure to produce more efficient animals has been a consistent challenge in livestock production. With advances in genetic selection and production sustainability, producers have been able to create more animal-based products from fewer animals in record time (Michalk et al., 2019). However, with expected global population growth and continuously changing food preferences, the livestock industry will continue to increase production output (Bodirsky et al., 2015). Precision livestock farming (PLF) aims to aid producers in this goal by incorporating the use of on-farm technology for improving animal welfare, health, production, and environmental sustainability through automated real-time monitoring of animals and their environment (Berckmans, 2014). The development of PLF tools, or precision technologies, through research can help to create useful devices in production settings that can help livestock producers optimize their time and give real-time warnings when welfare or health concerns related to their animals arise (Berckmans, 2017).

The use of precision technologies can have many practical applications in livestock production. Animal monitoring can be performed using many types of precision technologies, such as cameras and image analysis, microphone and sound analysis, and sensors (Berckmans, 2014; Berckmans, 2017). For example, real-time image analysis of dairy cattle has been used to help identify early warning signs of lameness, a major welfare concern in dairy production (Viazzi et al., 2013). The software used in this lameness detection technology calculates a body movement pattern for each cow exiting the milking parlor and classifies their gait to a lameness category (*i.e.*, not lame, lame, severely lame). If a cow's gait deviates from her previous records, the system automatically alerts the producer. This technology can help producers optimize their time and implement early intervention strategies to treat before lameness in their herd becomes detrimental or severe. Other precision technologies, like infrared thermal imaging, can aid in identifying sick or stressed animals by measuring animal skin temperature (Stewart et al., 2005; Cook et al., 2015). Within many livestock species, infrared thermal imaging has also been beneficial in the early detection of febrile diseases (Cook et al., 2015; Rainwater-Lovett et al., 2014), lameness (Amezcua et al., 2014; Alsaaod et al., 2015), as well as evaluating stress response from routine husbandry procedures (Stewart et al., 2005; Stewart, 2008). Additionally, individual identification technologies (*e.g*. RFID) allow producers to track animal feeding behaviors (Benjamin and Yik, 2019; Costa et al., 2021) and identify deviations in feed consumption.

Ultimately, precision technologies give producers an opportunity to monitor animal welfare on an individual-animal level. These technologies also offer limited contact with the animal to prevent disruption of their natural behavior and reduce animal stress commonly associated with routine examinations of animal health (*e.g.*, blood collections, weighing, etc.). Therefore, precision tools which have been used in animal welfare monitoring could be beneficial for characterizing the social hierarchy in groups of gestating sows.

1.5.1. Potential Precision Tools for Detecting the Social Hierarchy Within Group-Housed Pen Gestation Systems

1.5.1.1. Radio frequency identification technology

Radio frequency identification technology can be used within a livestock production system to identify individual animals (Brown-Brandl et al., 2019) through the use of ear tags containing microchips with unique serial number identifiers. The RFID ear tag holds a transponder circuit that emits radio waves to an RFID reader. Once the RFID reader has received the radio wave, it can immediately identify individual animals and collect data that can be stored and viewed at a later time (Benjamin and Yik, 2019). For example, RFID technology has been utilized to monitor livestock behavior to detect changes or disruptions in individual behavior associated with welfare challenges (*e.g.,* illness) (Brown-Brandl et al., 2019). These developments have resulted in improved farm management practices and animal welfare (Ruhil et al., 2013).

Electronic sow feeding systems equipped with RFID technology have been used within group gestation housing systems since the 1980s (Remience et al., 2008). Because the goal of group gestation housing is to offer sows the ability to move freely and perform natural behaviors, an ESF system allows for sows to visit the feeder when they desire (Jensen et al., 1995). Once a sow's ear tag RFID transponder is detected, feed can be dispensed in a bowl for the sow to consume. The feeding spaces offered by an ESF in group housing can range from 1 - 4 spaces per pen. The recommendation for the number of sows per feeder differs, with some manufacturers recommending 10 sows per feeding station and others stating their system can accommodate between 60 - 120 sows (National Hog Farmer, 2011). One disadvantage to the ESF feeding method is that sows can access the feeder whenever desired but do not have to exit at any specific point. This can limit other sows' access to the feeder and affect their ration consumption. Multiple sows can wait to access the feeder, but it does not guarantee their access, which can lead to impaired body weight gain, reproductive success, and poor welfare.

Due to the competitiveness created through the ESF system, certain feeding characteristics can be used to identify attributes associated with social ranking within the gestation herd. Research has found that dominant sows access the feeder earlier, spend longer lengths of time in ESF feeding stations, and visit the feeder more frequently compared to lower ranking sows (Martin and Edwards, 1994; Chapinal et al., 2010; Salak-Johnson, 2017). Low ranking sows obtain access to the feeder last (O'Connell et al., 2003), gain less weight in restricted feeding systems (Brouns and Edwards, 1994; Kranendonk et al., 2007; Salak-Johnson, 2017), and have lower feed intake (Salak-Johnson, 2017) compared to higher ranking sows. However, further research should investigate the relationship between social rank and feeding behavior to determine whether the social hierarchy can be characterized using RFID feeding system technology.

1.5.1.2. Infrared thermal imaging

Another precision tool which has been studied to aid in management of livestock health and welfare is infrared thermal imaging, or infrared thermography (IRT). Infrared thermal technology is predicated on the fact that any object which has a temperature above absolute zero (0 K or -273.15 ºC) emits infrared radiation. Infrared radiation wavelengths vary from 700 nm – 1 mm and the temperature of the object determines the wavelength emitted (Benjamin and Yik, 2019). Thermal imaging converts radiated wavelengths (*i.e*. the radiant heat of an object) into a color image that can be viewed through computer technology (Kateb et al., 2009; Vollmer and Mollmann, 2017). Although IRT is affected by many environmental factors (*i.e*., ambient temperature, relative humidity, sunlight, and foreign objects on the skin surface), infrared thermal imaging provides a quick, non-contact method that can be used to identify physiological and pathological changes in the body that are reflected in changes to body temperature (Salles et al., 2016).

Thermal imaging has the ability to reduce stress associated with a traditional animal health evaluation (*e.g*., animal restraint or injection) and can detect disease through automatic surveillance of changes to skin temperature (Soerensen and Pedersen, 2015). For example, one study found that growing pigs inoculated with *Actinobacillus pleuropneumoniea* exhibited increased rectal and mean body surface temperature compared to those who received no immune challenge (Loughmiller et al., 2001). In a similar study utilizing the same bacteria, body surface temperature surrounding the thoracic cavity region was higher in pigs on day 4 after inoculation, likely due to an increase in pulmonary inflammation (Menzel et al., 2014). In weaned piglets injected with a 3-way vaccination to imitate an immune challenge, infrared thermal images were able to identify a significant temperature difference in groups of piglets given the vaccine compared to both control and sham treatment groups, with vaccinated piglets having higher body surface temperature for 3 to 20 hours post-vaccination (Cook et al., 2015). Taken together, the results of these studies indicate that thermal imaging can detect febrile responses to disease and immune challenges in swine. As a result, animal caretakers better identify sick animals in need of treatment.

In addition to disease detection, IRT may be useful for detecting physiological stress experienced by pigs on farm. For example, the physiological processes that occur during episodes of stress may cause stressed induced hyperthermia and the release of catecholamines and cortisol, which can increase blood flow and lead to increased heat loss. These changes to core body temperature can be observed as heat loss through the skin (Stewart et al., 2005) which can be visualized using infrared thermal imaging. Previous studies evaluating pig handling styles (*i.e.,* gentle or rough), reported pigs handled in a rough manner exhibited increased body surface temperature in the region behind the ear, an anatomical location shown to be reliable when measuring the body surface temperature in swine due to its lack of fat deposition and hair (Rocha et al., 2019; Farrar et al., 2020).

Infrared thermal imaging may also be a helpful tool for evaluating the physiological stress response that occurs during social interactions between animals. However, little research involving pigs has evaluated the effect of agonistic interactions on body surface temperature using IRT. One study reported altered body surface temperature in response to aggressive interactions, but no differences were found in IRT characteristics between winners and losers of aggressive encounters (Boileau et al., 2019). Further research on this topic is needed to confirm whether IRT could be useful for the purpose of detecting social hierarchy. However, this technology could possibly demonstrate differences in body surface temperature between social ranks since changes in body temperature have been reported in response to handling stress and after aggressive interactions.

1.5.1.3. Heart rate monitors and automated heart rate detection technologies

One potential technology that may be useful for precision livestock monitoring in the future is automated collection of heart rate (HR) data and measurement of heart rate variability (HRV). Compared to solely measuring mean HR, HRV can be used as a more informative proxy of autonomic nervous system (ANS) function in response to stress. The ANS is an element of the peripheral nervous system that regulates involuntary physiological processes, such as HR and blood pressure (McCorry, 2007). These involuntary changes (mediated by the sympathetic and parasympathetic branches of the ANS) allow the cardiovascular system to adjust to sudden physical and psychological challenges that interrupt homeostasis (Shaffer et al., 2014). Heart rate variability evaluates changes to ANS function by measuring the variation in time between adjacent heart beats (also known as RR intervals; Shaffer et al., 2014) and is often used as a measure of physiological stress in livestock species (De Jong et al., 2000; Kovács et al., 2014).

Increased variation in time between adjacent heart beats is indicative of reduced stress as it reflects greater parasympathetic nervous system activity occurring within regulatory autonomic nervous system balance (Stauss, 2003; von Borell et al., 2007). Heart rate variability has been used to evaluate the stress response in pigs after exposure to a short heat episode, where growing pigs exposed to heat exhibited evidence of greater stress (Byrd et al., 2020). Additionally, studies evaluating gestating sows have shown that HRV is reduced in response to progressing gestation (Marchant-Forde and Marchant-Forde, 2004; Byrd et al., 2022), which indicates a shift away from parasympathetic activity.

While HRV is a promising methodology, little work has been conducted to determine its usefulness for evaluating stress resulting from social interactions. Some previous work evaluating mean HR and HRV to evaluate social stress (*e.g.*, food competition and residentintruder tests) in growing pigs reported that social status based on outcomes of agonistic encounters during food competition tests could influence mean HR measures, but no differences were found in HRV indices between winners and losers of aggressive encounters (De Jong et al., 2000). Another study found that sows' peak mean HR value increased during aggressive encounters (Marchant et al., 1995). The loser of the encounter experienced the highest peak HR after retreating, indicating aggressive interactions do cause a physiological response with the response being greater in sows that lose the encounter (Marchant et al., 1995).

Heart rate collection technologies have improved over time with the production of non-invasive, wearable monitors that can be fitted around the chest to collect various HR data measures. For humans, the monitor is placed in the middle of the chest, while monitors worn by animals must be placed on the left side of the chest, close to the elbow (Marchant-Forde et al., 2004; Mott et al., 2021). Although wearable monitors offer an easy-to-use tool to aid in quantifying physiological response to stress in animals (Mott et al., 2021), HR monitors are prone to error due to animal movement or animal interaction with pen mates or equipment. As a result, large data losses can occur if personnel are not present to monitor data collection. Therefore, given the challenges of wearable HR monitors in animal science research, an automated HR detection system is still in needed to be beneficial in evaluating the cardiac response to environmental stressors without worry of data loss due to equipment placement or removal during data collection. Recently published research exploring HR monitoring through video-based technology has indicated that automated HR technology may be a viable option in the future (Pai et al., 2021; Wang et al., 2021).

Given the usefulness of HRV for evaluating autonomic function in response to different stressors, additional research is needed to evaluate the sow HRV response to social stress.

Specifically, research investigating how social hierarchy affects HRV may be able to determine whether automated HRV detection can be used for identifying sows at risk of poor welfare states within the group pen, or as a predictor of social rank prior to mixing groups of sows.

1.6. Conclusion

Animal welfare concerns regarding physiology, reproductive performance, and injuries due to the establishment of the social hierarchy within group gestation housing can arise and also impact animal productivity. The ability to identify the social hierarchy could be advantageous for producers and caretakers when managing gestating sows. One potential strategy for aiding producers in identifying the sow social hierarchy may be through the use of precision livestock farming tools, which can detect warning signs related to animal welfare.

Therefore, the objective of this thesis was to investigate the use of IRT, feeding activity obtained from an automated RFID feeding system, and HRV indices for detecting the social hierarchy within groups of gestating sows. Additionally, the relationship between observed social hierarchy, body condition scores (BCS), backfat (BF), and reproductive performance was also explored.

1.7. References

Alsaaod, M., A. L. Schaefer, W. Büscher, and A. Steiner. 2015. The role of infrared thermography as a non-invasive tool for the detection of lameness in cattle. Sensors (Switzerland). 15:14513–14525. doi:10.3390/s150614513.

Alworth, L. C., and S. C. Buerkle. 2013. The effects of music on animal physiology, behavior and welfare. Lab Anim. (NY). 42:54–61. doi:10.1038/laban.162.

Amezcua, R., S. Walsh, P. H. Luimes, and R. M. Friendship. 2014. Infrared thermography to evaluate lameness in pregnant sows. Can. Vet. J. 55:268–272.

Anil, L., S. S. Anil, J. Deen, K. Samuel, and J. E. Wheaton. 2005. Evaluation of well-being, productivity, and and longevity of pregnant sows housed or separately in gestation stalls. Am. J. Vet. Res. 66.

Arey, D. S., and S. A. Edwards. 1998. Factors influencing aggression between sows after mixing and the consequences for welfare and production. Livest. Prod. Sci. 56:61–70. doi:10.1016/S0301-6226(98)00144-4.

Barnett, J. L., P. H. Hemsworth, G. M. Cronin, E. C. Jongman, and G. D. Hutson. 2001. A review of the welfare issues for sows and piglets in relation to housing. Aust. J. Agric. Res. 4:269–281.

Bates, R. O., D. B. Edwards, and R. L. Korthals. 2003. Sow performance when housed either in groups with electronic sow feeders or stalls. Livest. Prod. Sci. 79:29–35. doi:10.1016/S0301-6226(02)00119-7.

Beaver, A., K. L. Proudfoot, and M. A. G. von Keyserlingk. 2020. Symposium review: considerations for the future of dairy cattle housing: An animal welfare perspective. J. Dairy Sci. 103:5746–5758. doi:10.3168/jds.2019-17804.

Bench, C. J., F. C. Rioja-Lang, S. M. Hayne, and H. W. Gonyou. 2013. Group gestation housing with individual feeding-I: how feeding regime, resource allocation, and genetic factors affect sow welfare. Livest. Sci. 152:208–217. doi:10.1016/j.livsci.2012.12.021.

Benjamin, M., and S. Yik. 2019. Precision livestock farming in swine welfare: A review for swine practitioners. Animals. 9:1–21. doi:10.3390/ani9040133.

Berckmans, D. 2014. Precision livestock farming technologies for welfare management in intensive livestock systems. OIE Rev. Sci. Tech. 33:189–196. doi:10.20506/rst.33.1.2273.

Berckmans, D. 2017. General introduction to precision livestock farming. Anim. Front. 7:6–11. doi:10.2527/af.2017.0102.

Bodirsky, B. L., S. Rolinski, A. Biewald, I. Weindl, A. Popp, and H. & Lotze-Campen. 2015. Global foor demand scenarios for the 21st century. PLoS One. 10:1–27. doi:doi.org/10.1371/journal.pone.0139201.

Boileau, A., M. Farish, S. P. Turner, and I. Camerlink. 2019. Infrared thermography of agonistic behaviour in pigs. Physiol. Behav. 210:112637. doi:10.1016/j.physbeh.2019.112637.

von Borell, E., J. Langbein, G. Després, S. Hansen, C. Leterrier, J. Marchant-Forde, R. Marchant-Forde, M. Minero, E. Mohr, A. Prunier, D. Valance, and I. Veissier. 2007. Heart rate variability as a measure of autonomic regulation of cardiac activity for assessing stress and welfare in farm animals - a review. Physiol. Behav. 92:293–316. doi:10.1016/j.physbeh.2007.01.007.

Bracke, M. B. M., and H. Hopster. 2006. Assessing the importance of natural behavior for animal welfare. J. Agric. Environ. Ethics. 19:77–89. doi:10.1007/s10806-005-4493-7.

Broom, D. 2017. Cortisol: often not the best indicator of stress and poor welfare. Physiol. News. 30–32.

Broom, D. M. 1986. Indicators of poor welfare. Br. Vet. J. 142:524–526.

Broom, D. M. 1988. The scientific assessment of animal welfare. Appl. Anim. Behav. Sci. 20:5–19. doi:10.1016/0168-1591(88)90122-0.

Broom, D. M. 1991. Animal welfare: concepts and measurement. J. Anim. Sci. 69:4167–4175. doi:10.2527/1991.69104167x.

Broom, D. M. 2010. Cognitive ability and awareness in domestic animals and decisions about obligations to animals. Appl. Anim. Behav. Sci. 126:1–11. doi:10.1016/j.applanim.2010.05.001.

Broom, D. M. 2011. A history of animal welfare science. Acta Biotheor. 59:121–137. doi:10.1007/s10441-011-9123-3.

Brouns, F., and S. A. Edwards. 1994. Social rank and feeding behaviour of group-housed sows fed competitively or ad libitum. Appl. Anim. Behav. Sci. 39:225–235. doi:10.1016/0168-1591(94)90158-9.

Brown-Brandl, T. M., F. Adrion, J. Maselyne, A. Kapun, E. F. Hessel, W. Saeys, A. Van Nuffel, and E. Gallmann. 2019. A review of passive radio frequency identification systems for animal monitoring in livestock facilities. Am. Soc. Agric. Biol. Eng. 35:579–591.

Browning, H. 2020. The Natural Behavior Debate: Two Conceptions of Animal Welfare. J. Appl. Anim. Welf. Sci. 23:325–337. doi:10.1080/10888705.2019.1672552.

Buchanan, T. W., M. Al’Absi, and W. R. Lovallo. 1999. Cortisol fluctuates with increases and decreases in negative affect. Psychoneuroendocrinology. 24:227–241. doi:10.1016/S0306-4530(98)00078-X.

Byrd, C. J., J. S. Johnson, J. S. Radcliffe, B. A. Craig, S. D. Eicher, and D. C. Lay. 2020. Nonlinear analysis of heart rate variability for evaluating the growing pig stress response to an acute heat episode. Animal. 14:379–387. doi:10.1017/S1751731119001630.

Byrd, C. J., B. R. McConn, B. N. Gaskill, A. P. Schinckel, A. R. Green-Miller, D. C. Lay, and J. S. Johnson. 2022. Characterizing the effect of incrementally increasing dry bulb temperature on linear and nonlinear measures of heart rate variability in nonpregnant, mid-gestation, and late-gestation sows. J. Anim. Sci. 100:1–9. doi:10.1093/jas/skac004.

Chapinal, N., J. L. Ruiz de la Torre, A. Cerisuelo, J. Gasa, M. D. Baucells, J. Coma, A. Vidal, and X. Manteca. 2010. Evaluation of welfare and productivity in pregnant sows kept in stalls or in 2 different group housing systems. J. Vet. Behav. Clin. Appl. Res. 5:82–93. doi:10.1016/j.jveb.2009.09.046.

Childers, H., P. B. Thompson, J. Kellogg, J. Deen, S. S. Anil, L. Anil, M. C. Appleby, H. W. Gonyou, and E. A. Pajor. 2004. Animal Welfare Forum: sow housing and welfare.

Cook, N. J., B. Chabot, T. Lui, C. J. Bench, and A. L. Schaefer. 2015. Infrared thermography detects febrile and behavioural responses to vaccination of weaned piglets. Animal. 9:339–348. doi:10.1017/S1751731114002481.

Costa, J. H. C., M. C. Cantor, and H. W. Neave. 2021. Symposium review: Precision technologies for dairy calves and management applications. J. Dairy Sci. 104:1203–1219. doi:10.3168/jds.2019-17885.

Council Directive 2008/120/EC. 2009. Laying down minimum standards for the protection of pigs. Official J. European Union. 18.2.2009.

Council, C. C. P. (2014). Code of practice for the care and handling of pigs. Canada Pork Council and National Farm Animal Care Council. p. 48.

Dawkins, M. S. 2006. A user’s guide to animal welfare science. Trends Ecol. Evol. 21:77–82. doi:10.1016/j.tree.2005.10.017.

Désiré, L., A. Boissy, and I. Veissier. 2002. Emotions in farm animals: a new approach to animal welfare in applied ethology. Behav. Processes. 60:165–180. doi:10.1016/s0376-6357(02)00081-5.

Duncan, I. J. H., and M. S. Dawkins. 1983. The problem of assessing “well-being” and “suffering” in farm animals. Indic. Relev. to farm Anim. Welf. 13–24.

Duncan, I. J., and J. C. Petherick. 1991. The implications of cognitive processes for animal welfare. J. Anim. Sci. 69:5017–5022. doi:10.2527/1991.69125017x.

Einarsson, S., A. Madej, and V. Tsuma. 1996. The influence of stress on early pregnancy in the pig. Anim. Reprod. Sci. 42:165–172. doi:10.1016/0378-4320(96)01516-3.

Farrar, K. L., A. E. Field, S. L. Norris, and K. O. Jacobsen1. 2020. Comparison of rectal and infrared thermometry temperatures in anesthetized swine (sus scrofa). J. Am. Assoc. Lab. Anim. Sci. 59:221–225. doi:10.30802/AALAS-JAALAS-19-000119.

Forrester, R. 1980. Stereotypies and the behavioral regulation of motivational state. Appl. Anim. Behav. Sci. 6:386–387.

Fraser, D. 2003. Assessing animal welfare at the farm and group level: the interplay of science and values. Anim. Welf. 12:433–443.

Fraser, D. 2008. Understanding animal welfare. Acta Vet. Scand. 50:1–7. doi:10.1186/1751-0147-50-S1-S1.

Fraser, D., D. M. Weary, E. A. Pajor, B. N. Milligan, and & Milligan. 1997. A scientific conception of animal welfare that reflects ethical concerns. WBI Stud. Repos. Animal Wel:187–205.

Green, T. C., and D. J. Mellor. 2011. Extending ideas about animal welfare assessment to include "quality of life" and related concepts. N. Z. Vet. J. 59:263–271. doi:10.1080/00480169.2011.610283.

Greenwood, E. C., K. J. Plush, W. H. E. J. van Wettere, and P. E. Hughes. 2014. Hierarchy formation in newly mixed, group housed sows and management strategies aimed at reducing its impact. Appl. Anim. Behav. Sci. 160:1–11. doi:10.1016/j.applanim.2014.09.011.

Harris, M. J., E. A. Pajor, A. D. Sorrells, S. D. Eicher, B. T. Richert, and J. N. Marchant-Forde. 2006. Effects of stall or small group gestation housing on the production, health and behaviour of gilts. Livest. Sci. 102:171–179. doi:10.1016/j.livsci.2005.12.004.

Held, S. D. E., and M. Špinka. 2011. Animal play and animal welfare. Anim. Behav. 81:891–899. doi:10.1016/j.anbehav.2011.01.007.

Hemsworth, P. H. 2018a. Key determinants of pig welfare: implications of animal management and housing design on livestock welfare. Anim. Prod. Sci. 58:1375–1386. doi:10.1071/AN17897.

Hemsworth, Paul H. 2018b. Defining and ensuring animal welfare in pig production: an overview. 125–150. doi:10.19103/as.2017.0013.19.

Hemsworth, P. H., J. L. Barnett, and C. Hansen. 1987. The influence of inconsistent handling by humans on the behaviour, growth and corticosteroids of young pigs. Appl. Anim. Behav. Sci. 17:245–252. doi:10.1016/0168-1591(87)90149-3.

Hemsworth, P. H., D. J. Mellor, G. M. Cronin, and A. J. Tilbrook. 2015. Scientific assessment of animal welfare. N. Z. Vet. J. 63:24–30. doi:10.1080/00480169.2014.966167.

Hemsworth, P. H., R. S. Morrison, A. J. Tilbrook, K. L. Butler, M. Rice, and S. J. Moeller. 2016. Effects of varying floor space on aggressive behavior and cortisol concentrations in group-housed sows. J. Anim. Sci. 94:4809–4818. doi:10.2527/jas.2016-0583.

Hemsworth, P. H., M. Rice, J. Nash, K. Giri, K. L. Butler, A. J. Tilbrook, and R. S. Morrison. 2013. Effects of group size and floor space allowance on grouped sows: aggression, stress, skin injuries, and reproductive performance. J. Anim. Sci. 91:4953–4964. doi:10.2527/jas.2012-5807.

Honeyman, M. S., R. S. Pirog, G. H. Huber, P. J. Lammers, and J. R. Hermann. 2006. The United States pork niche market phenomenon. J. Anim. Sci. 84:2269–2275. doi:10.2527/jas.2005-680.

Horback, K. 2014. Nosing Around: Play in Pigs. Anim. Behav. Cogn. 2:186. doi:10.12966/abc.05.08.2014.

Horback, K. M., and T. D. Parsons. 2019. Judgement bias testing in group-housed gestating sows. Behav. Processes. 159:86–92. doi:10.1016/j.beproc.2018.12.021.

HSVMA. 2013. Humane Society Veterinary Medical Association (HSVMA) Veterinary report on gestation crates.

Iida, R., C. Piñeiro, and Y. Koketsu. 2017. Behavior, displacement and pregnancy loss in pigs under an electronic sow feeder. J. Agric. Sci. 9:43. doi:10.5539/jas.v9n12p43.

Jang, J. C., S. W. Jung, S. S. Jin, S. J. Ohh, J. E. Kim, and Y. Y. Kim. 2015. The effects of gilts housed either in group with the electronic sow feeding system or conventional stall. Asian-Australasian J. Anim. Sci. 28:1512–1518. doi:10.5713/ajas.14.0819.

Jensen, K. H., B. K. Pedersen, L. J. Pedersen, and E. Jargensen. 1995. Well-being in pregnant sows: confinement versus group housing with electronic sow feeding. Acta Agric. Scand. Sect. B Soil Plant Sci. 45:266–275. doi:10.1080/09064709509413086.

Jensen, P. 1980. An ethogram of social interaction patterns in group-housed dry sows. Appl. Anim. Ethol. 6:341–350. doi:10.1016/0304-3762(80)90134-0.

De Jong, I. C., A. Sgoifo, E. Lambooij, S. M. Korte, H. J. Blokhuis, and J. M. Koolhaas. 2000. Effects of social stress on heart rate and heart rate variability in growing pigs. Can. J. Anim. Sci. 80:273–280. doi:10.4141/a99-085.

de Jonge, J., and H. C. M. van Trijp. 2013. Meeting heterogeneity in consumer demand for animal welfare: a reflection on existing knowledge and implications for the meat sector.

Karlen, G. A. M., P. H. Hemsworth, H. W. Gonyou, E. Fabrega, A. David Strom, and R. J. Smits. 2007. The welfare of gestating sows in conventional stalls and large groups on deep litter. Appl. Anim. Behav. Sci. 105:87–101. doi:10.1016/j.applanim.2006.05.014.

Kateb, B., V. Yamamoto, C. Yu, W. Grundfest, and J. P. Gruen. 2009. Infrared thermal imaging: a review of the literature and case report. Neuroimage. 47:T154–T162. doi:10.1016/j.neuroimage.2009.03.043.

Kemp, B., and N. M. Soede. 2012. Reproductive issues in welfare-friendly housing systems in pig husbandry: a review. Reprod. Domest. Anim. 47:51–57. doi:10.1111/j.1439-0531.2012.02108.x.

Kiley-Worthington, M. 1989. Ecological, ethological, and ethically sound environments for animals: toward symbiosis. J. Agric. Ethics. 2:323–347. doi:10.1007/BF01826810.

Koketsu, Y., and R. Iida. 2017. Sow housing associated with reproductive performance in breeding herds. Mol. Reprod. Dev. 84:979–986. doi:10.1002/mrd.22825.

Kovács, L., V. Jurkovich, M. Bakony, O. Szenci, P. Póti, and J. Tå'Zsér. 2014. Welfare implication of measuring heart rate and heart rate variability in dairy cattle: literature review and conclusions for future research. Animal. 8:316–330. doi:10.1017/S1751731113002140.

Kranendonk, G., H. Van Der Mheen, M. Fillerup, and H. Hopster. 2007. Social rank of pregnant sows affects their body weight gain and behavior and performance of the offspring. J. Anim. Sci. 85:420–429. doi:10.2527/jas.2006-074.

Langbein, J., and B. Puppe. 2004. Analysing dominance relationships by sociometric methods - a plea for a more standardised and precise approach in farm animals. Appl. Anim. Behav. Sci. 87:293–315. doi:10.1016/j.applanim.2004.01.007.

Lay Jr., D. C., M. F. Haussmann, and M. J. Daniels. 2000. Hoop housing for feeder pigs offers a welfare-friendly environment compared to a nonbedded confinement system. J. Appl. Anim. Welf. Sci. 3:33–48. doi:10.1207/s15327604jaws0301_4.

Li, Y. Z., S. Q. Cui, X. J. Yang, L. J. Johnston, and S. K. Baidoo. 2018. Minimal floor space allowance for gestating sows kept in pens with electronic sow feeders on fully slatted floors. J. Anim. Sci. 96:4195–4208. doi:10.1093/jas/sky282.

Liu, X., P. Song, H. Yan, L. Zhang, L. Wang, L. S. Fuping Zhao Xinhua Hou, B. Li, and and L. Wang. 2021. A comparison of the behavior, physiology, and offspring resilience of gestating sows when raised in a group housing system and individual stalls. Animals. 11:2076. doi:https://doi.org/10.3390/ani11072076.

Loughmiller, J. A., M. E. Spire, S. S. Dritz, B. W. Fenwick, M. H. Hosni, and S. B. Hogge. 2001. Relationship between mean body surface temperature measured by use of infrared thermography and ambient temperature in clinically normal pigs and pigs inoculated with Actinobacillus pleuropneumoniae. Am. J. Vet. Res. 62:676–681. doi:10.2460/ajvr.2001.62.676.

Mack, L. A., D. C. Lay, S. D. Eicher, A. K. Johnson, B. T. Richert, and E. A. Pajor. 2014. Group space allowance has little effect on sow health, productivity, or welfare in a free-access stall system. J. Anim. Sci. 92:2554–2567. doi:10.2527/jas.2013-7352.

Maes, D., L. Pluym, and O. Peltoniemi. 2016. Impact of group housing of pregnant sows on health. Porc. Heal. Manag. 2:1–7. doi:10.1186/s40813-016-0032-3.

Marchant-Forde, J., and R. M. Marchant-Forde. 2005. Minimizing inter-pig aggression during mixing. Pig News Inf. 26:63–71.

Marchant-Forde, J. N. 2015. The science of animal behavior and welfare: challenges, opportunities, and global perspective. Front. Vet. Sci. 2. doi:10.3389/fvets.2015.00016.

Marchant-Forde, R. M., and J. N. Marchant-Forde. 2004. Pregnancy-related changes in behavior and cardiac activity in primiparous pigs. Physiol. Behav. 82:815–825. doi:10.1016/j.physbeh.2004.06.021.

Marchant-Forde, R. M., D. J. Marlin, and J. N. Marchant-Forde. 2004. Validation of a cardiac monitor for measuring heart rate variability in adult female pigs: accuracy, artefacts and editing. Physiol. Behav. 80:449–458. doi:10.1016/j.physbeh.2003.09.007.

Marchant, J. N., M. T. Mendl, A. R. Rudd, and D. M. Broom. 1995. The effect of agonistic interactions on the heart rate of group-housed sows. Appl. Anim. Behav. Sci. 46:49–56. doi:10.1016/0168-1591(95)00636-2.

Martin, J. E., and S. A. Edwards. 1994. Feeding behaviour of outdoor sows: the effects of diet quantity and type. Appl. Anim. Behav. Sci. 41:63–74. doi:10.1016/0168-1591(94)90052-3.

Maselyne, J., W. Saeys, and A. Van Nuffel. 2015. Review: quantifying animal feeding behaviour with a focus on pigs. Physiol. Behav. 138:37–51. doi:10.1016/j.physbeh.2014.09.012.

Mason, G. J. 1991. Stereotypies and suffering. Behav. Processes. 25:103–115. doi:10.1016/0376-6357(91)90013-P.

Mason, Georgia J. 1991. Stereotypies: a critical review. Anim. Behav. 41:1015–1037. doi:10.1016/S0003-3472(05)80640-2.

Matthews, L. R., and P. H. Hemsworth. 2012. Drivers of change: law, international markets, and policy. Anim. Front. 2:40–45. doi:10.2527/af.2012-0047.

McCorry, L. K. 2007. Physiology of the autonomic nervous system. Am. J. Pharm. Educ. 71:1–11. doi:10.1111/j.1399-6576.1964.tb00252.x.

Mcglone, J. J. 1986. Influence of resources on pig aggression and dominance. Behav. Processes. 12:135–144.

McGlone, J. J. 2001. Farm animal welfare in the context of other society issues: Toward sustainable systems. Livest. Prod. Sci. 72:75–81. doi:10.1016/S0301-6226(01)00268-8.

McGlone, J. J. 2013. Review: Updated scientific evidence on the welfare of gestating sows kept in different housing systems. Prof. Anim. Sci. 29:189–198. doi:10.15232/S1080-7446(15)30224-2.

Meese, G. B., and R. Ewbank. 1973. The establishment and nature of the dominance hierarchy in the domesticated pig. Anim. Behav. 21:326–334. doi:10.1016/S0003-3472(73)80074-0.

Mellor, D. J. 2015. Enhancing animal welfare by creating opportunities for positive affective engagement. N. Z. Vet. J. 63:3–8. doi:10.1080/00480169.2014.926799.

Mellor, D. J. 2017. Operational details of the five domains model and its key applications to the assessment and management of animal welfare. Animals. 7. doi:10.3390/ani7080060.

Mellor, D. J., and N. J. Beausoleil. 2015. Extending the “Five Domains” model for animal welfare assessment to incorporate positive welfare states. Anim. Welf. 24:241–253. doi:10.7120/09627286.24.3.241.

Mellor, D. J., and J. R. Webster. 2014. Development of animal welfare understanding drives change in minimum welfare standards. OIE Rev. Sci. Tech. 33:121–130. doi:10.20506/rst.33.1.2258.

Mench, J. A. 2008. Farm animal welfare in the U.S.A.: farming practices, research, education, regulation, and assurance programs. Appl. Anim. Behav. Sci. 113:298–312. doi:10.1016/j.applanim.2008.01.009.

Mendl, M., O. H. P. Burman, and E. S. Paul. 2010. An integrative and functional framework for the study of animal emotion and mood. Proc. R. Soc. B Biol. Sci. 277:2895–2904. doi:10.1098/rspb.2010.0303.

Mendl, M., A. J. Zanella, and D. M. Broom. 1992. Physiological and reproductive correlates of behavioural strategies in female domestic pigs. Anim. Behav. 44:1107–1121. doi:10.1016/S0003-3472(05)80323-9.

Menzel, A., M. Beyerbach, C. Siewert, M. Gundlach, D. Hoeltig, R. Graage, H. Seifert, K. H. Waldmann, J. Verspohl, and I. Hennig-Pauka. 2014. Actinobacillus pleuropneumoniae challenge in swine: Diagnostic of lung alterations by infrared thermography. BMC Vet. Res. 10:1–13. doi:10.1186/s12917-014-0199-2.

Michalk, D. L., D. R. Kemp, W. B. Badgery, J. Wu, Y. Zhang, and P. J. Thomassin. 2019. Sustainability and future food security—a global perspective for livestock production. L. Degrad. Dev. 30:561–573. doi:10.1002/ldr.3217.

Mott, R., F. Dowell, and N. Evans. 2021. Use of the Polar V800 and Actiheart 5 heart rate monitors for the assessment of heart rate variability (HRV) in horses. Appl. Anim. Behav. Sci. 241:5–10. doi:10.1016/j.applanim.2021.105401.

Mount, N. C., and M. F. Seabrook. 1993. A study of aggression when group housed sows are mixed. Appl. Anim. Behav. Sci. 36:377–383. doi:10.1016/0168-1591(93)90134-B.

Munsterhjelm, C., A. Valros, M. Heinonen, O. Hälli, and O. A. T. Peltoniemi. 2008. Housing during early pregnancy affects fertility and behaviour of sows. Reprod. Domest. Anim. 43:584–591. doi:10.1111/j.1439-0531.2007.00956.x.

Murphy, E., R. E. Nordquist, and F. J. van der Staay. 2014. A review of behavioural methods to study emotion and mood in pigs, Sus scrofa. Appl. Anim. Behav. Sci. 159:9–28. doi:10.1016/j.applanim.2014.08.002.

Nääs, I. A., R. G. Garcia, and F. R. Caldara. 2014. Infrared thermal image for assessing animal health and welfare. J. Anim. Behav. Biometeorol. 2:66–72. doi:10.14269/2318-1265/jabb.v2n3p66-72.

Nalon, E., S. Conte, D. Maes, F. A. M. Tuyttens, and N. Devillers. 2013. Assessment of lameness and claw lesions in sows. Livest. Sci. 156:10–23. doi:10.1016/j.livsci.2013.06.003.

National Hog Farmer. 2011. Loose Sow Housing Gets Top Billing. Natl. Hog Farmer.

Norring, M., A. Valros, P. Bergman, J. N. Marchant-Forde, and M. Heinonen. 2019. Body condition, live weight and success in agonistic encounters in mixed parity groups of sows during gestation. Animal. 13:392–398. doi:10.1017/S1751731118001453.

NseaAbasi, N. E., E. A. O. Edem, G. D. Eyoh, and M. D. Udo. 2013. Stress and animal welfare: an uneasy relationship. Eur. J. Res. Med. Sci. 1:9–16.

O’Connell, N. E., V. E. Beattie, and B. W. Moss. 2003. Influence of social status on the welfare of sows in static and dynamic groups. Anim. Welf. 12:239–249.

Pacheco, E. 2016. Assessing the well-being of gestating submissive sows in group pens using multiple welfare metrics. doi.org/10.1016/j.jplph.2009.07.006%0A.

Pacheco, E., and J. L. Salak-Johnson. 2016. Social Status Affects Welfare Metrics of Group-Housed Gestating Sows. J. Vet. Res. Anim. Husb. 1:103.

Pai, A., A. Veeraraghavan, and A. Sabharwal. 2021. HRVCam: robust camera-based measurement of heart rate variability. J. Biomed. Opt. 26:1–23. doi:10.1117/1.jbo.26.2.022707.

Pérez de Diego, A. C., P. J. Sánchez-Cordón, M. Pedrera, B. Martínez-López, J. C. Gómez-Villamandos, and J. M. Sánchez-Vizcaíno. 2013. The use of infrared thermography as a non-invasive method for fever detection in sheep infected with bluetongue virus. Vet. J. 198:182–186. doi:10.1016/j.tvjl.2013.07.013.

Rainwater-Lovett, K., J. M. Pacheco, C. Packer, and L. L. Rodriguez. 2009. Detection of foot-and-mouth disease virus infected cattle using infrared thermography. Vet. J. 180:317–324. doi:10.1016/j.tvjl.2008.01.003.

Reimert, I., J. E. Bolhuis, B. Kemp, and T. B. Rodenburg. 2013. Indicators of positive and negative emotions and emotional contagion in pigs. Physiol. Behav. 109:42–50. doi:10.1016/j.physbeh.2012.11.002.

Reimert, I., J. E. Bolhuis, B. Kemp, and T. B. Rodenburg. 2015. Emotions on the loose: emotional contagion and the role of oxytocin in pigs. Anim. Cogn. 18:517–532. doi:10.1007/s10071-014-0820-6.

Remience, V., J. Wavreille, B. Canart, M. C. Meunier-Salaün, A. Prunier, N. Bartiaux-Thill, B. Nicks, and M. Vandenheede. 2008. Effects of space allowance on the welfare of dry sows kept in dynamic groups and fed with an electronic sow feeder. Appl. Anim. Behav. Sci. 112:284–296. doi:10.1016/j.applanim.2007.07.006.

Rhodes, R. T., M. C. Appleby, K. Chinn, L. Douglas, L. D. Firkins, K. A. Houpt, C. Irwin, J. J. McGlone, P. Sundberg, L. Tokach, and R. W. Wills. 2005. A comprehensive review of housing for pregnant sows. J. Am. Vet. Med. Assoc. 227:1580–1590. doi:10.2460/javma.2005.227.1580.

Ritter, C., A. Beaver, and M. A. G. von Keyserlingk. 2019. The complex relationship between welfare and reproduction in cattle. Reprod. Domest. Anim. 54:29–37. doi:10.1111/rda.13464.

Rocha, L. M., N. Devillers, X. Maldague, F. Z. Kabemba, J. Fleuret, F. Guay, and L. Faucitano. 2019. Validation of anatomical sites for the measurement of infrared body surface temperature variation in response to handling and transport. Animals. 9:1–18. doi:10.3390/ani9070425.

Ruhil, A. P., T. K. Mohanty, S. V. N. Rao, S. S. Lathwal, and V. Venkata Subramanian. 2013. Radio-frequency identification: A cost effective tool to improve livestock sector. Indian J. Anim. Sci. 83:871–879.

Rushen, J. 1984. Stereotyped behaviour, adjunctive drinking and the feeding periods of tethered sows. Anim. Behav. 32:1059–1067. doi:10.1016/S0003-3472(84)80222-5.

Rushen, J. 2003. Changing concepts of farm animal welfare: Bridging the gap between applied and basic research. Appl. Anim. Behav. Sci. 81:199–214. doi:10.1016/S0168-1591(02)00281-2.

Salak-Johnson, J. L. 2017. Social status and housing factors affect reproductive performance of pregnant sows in groups. Mol. Reprod. Dev. 84:905–913. doi:10.1002/mrd.22846.

Salak-Johnson, J. L., S. R. Niekamp, S. L. Rodriguez-Zas, M. Ellis, and S. E. Curtis. 2007. Space allowance for dry, pregnant sows in pens: Body condition, skin lesions, and performance. J. Anim. Sci. 85:1758–1769. doi:10.2527/jas.2006-510.

Salles, M. S. V., S. C. da Silva, F. A. Salles, L. C. Roma, L. El Faro, P. A. Bustos Mac Lean, C. E. Lins de Oliveira, and L. S. Martello. 2016. Mapping the body surface temperature of cattle by infrared thermography. J. Therm. Biol. 62:63–69. doi:10.1016/j.jtherbio.2016.10.003.

Scollo, A., F. Gottardo, B. Contiero, and S. A. Edwards. 2014. Does stocking density modify affective state in pigs as assessed by cognitive bias, behavioural and physiological parameters? Appl. Anim. Behav. Sci. 153:26–35. doi:10.1016/j.applanim.2014.01.006.

Shaffer, F., R. McCraty, and C. L. Zerr. 2014. A healthy heart is not a metronome: an integrative review of the heart's anatomy and heart rate variability. Front. Psychol. 5:1–19. doi:10.3389/fpsyg.2014.01040.

Soerensen, D. D., and L. J. Pedersen. 2015. Infrared skin temperature measurements for monitoring health in pigs: A review. Acta Vet. Scand. 57. doi:10.1186/s13028-015-0094-2.

Spoolder, H. A. M., M. J. Geudeke, C. M. C. Van der Peet-Schwering, and N. M. Soede. 2009. Group housing of sows in early pregnancy: a review of success and risk factors. Livest. Sci. 125:1–14. doi:10.1016/j.livsci.2009.03.009.

Stauss, H. M. 2003. Heart rate variability. Am. J. Physiol. Integr. Comp. Physiol. 285:R927–R931.

Stewart, M., J. R. Webster, A. L. Schaefer, N. J. Cook, and S. L. Scott. 2005. Infrared thermography as a non-invasive tool to study animal welfare. Anim. Welf. 14:319–325.

Stewart, M. 2008. Non-invasive measurment of stress and pain in cattle using infrared thermography: a thesis submitted in partial fulfillment of the requirements for the degreee of Doctor of Philosophy in Animal Science. Massey University, Palmerston North, New Zealand. p. 49-60.

Sutanto, W., and E. R. de Kloet. 1994. The use of various animal models in the study of stress and stress-related phenomena. Lab. Anim. 28:293–306. doi:10.1258/002367794780745092.

Tsuma, V. T., S. Einarsson, A. Madej, H. Kindahl, N. Lundeheim, and T. Rojkittikhun. 1996. Endocrine changes during group housing of primiparous sows in early pregnancy. Acta Vet. Scand. 37:481–490. doi:10.1186/BF03548088.

Vargovic, L., S. Hermesch, R. Z. Athorn, and K. L. Bunter. 2021. Feed intake and feeding behavior traits for gestating sows recorded using electronic sow feeders. J. Anim. Sci. 99:1–12. doi:10.1093/jas/skaa395.

Verdon, M., C. F. Hansen, J. L. Rault, E. Jongman, L. U. Hansen, K. Plush, and P. H. Hemsworth. 2015. Effects of group housing on sow welfare: a review. J. Anim. Sci. 93:1999–2017. doi:10.2527/jas.2014-8742.

Verdon, M., R. S. Morrison, M. Rice, and P. H. Hemsworth. 2016. Individual variation in sow aggressive behavior and its relationship with sow welfare. J. Anim. Sci. 94:1203–1214. doi:10.2527/jas.2015-0006.

Viazzi, S., C. Bahr, A. Schlageter-Tello, T. Van Hertem, C. E. B. Romanini, A. Pluk, I. Halachmi, C. Lokhorst, and D. Berckmans. 2013. Analysis of individual classification of lameness using automatic measurement of back posture in dairy cattle. J. Dairy Sci. 96:257–266. doi:10.3168/jds.2012-5806.

Vieuille-Thomas, C., G. Le Pape, and J. P. Signoret. 1995. Stereotypies in pregnant sows: indications of influence of the housing system on the patterns expressed by the animals. Appl. Anim. Behav. Sci. 44:19–27. doi:10.1016/0168-1591(95)00574-C.

Vollmer, M., and K.-P. Mollmann. 2017. Fundamentals of Infrared Thermal Imaging. In: Infrared Thermal Imaging Fundamentals, Research and Applications. Second. Wiley-VCH. p. 1–6.

Wang, M., A. Youssef, M. Larsen, J. L. Rault, D. Berckmans, J. N. Marchant-Forde, J. Hartung, A. Bleich, M. Lu, and T. Norton. 2021. Contactless video-based heart rate monitoring of a resting and an anesthetized pig. Animals. 11:1–14. doi:10.3390/ani11020442.

Webster, A. J. F. 2001. Farm animal welfare: the five freedoms and the free market. Vet. J. 161:229–237. doi:10.1053/tvjl.2000.0563.

Winckler, C., and S. Willen. 2001. The reliability and repeatability of a lameness scoring system for sse as an indicator of welfare in dairy cattle. Acta Agric. Scand. A Anim. Sci. 51:103–107. doi:10.1080/090647001316923162.

Zhao, Y., W. L. Flowers, A. Saraiva, K. J. Yeum, and S. W. Kim. 2013. Effect of social ranks and gestation housing systems on oxidative stress status, reproductive performance, and immune status of sows1. J. Anim. Sci. 91:5848–5858. doi:10.2527/jas.2013-6388.

2. ARE INFRARED THERMOGRAPHY, AUTOMATED FEEDING SYSTEMS, AND HEART RATE VARIABILITY MEASURES CAPABLE OF CHARACTERIZING GROUP HOUSED SOW SOCIAL HIERARCHIES?[1]

2.1. Introduction

Group gestation housing is quickly becoming standard practice in commercial swine production in the United States. Although this housing system is standard in the European Union, pork producers in the U.S are beginning to transition from housing gestating sows and gilts in individual stalls to placing breeding females in a group pen for a majority of their gestation phase. Group housing offers several benefits for sow welfare including improved behavioral variability and expression (Barnett et al., 2001; Elmore et al., 2011). However, the housing system can also lead to several management challenges for producers, such as injuries and poor performance, which are created after mixing and can last throughout gestation (Bench et al., 2013). Aggressive behavior among sows and gilts is expected during and shortly after mixing, as sows within groups fight in order to establish a social hierarchy (Arey and Edwards, 1998; Kirkwood and Zanella, 2005), a common social structure among livestock species (Sapolsky, 2004; Val-Laillet et al., 2008).

The establishment of a social hierarchy in mammalian species results from an individual's need for access to resources. For example, group gestation housing systems that utilize electronic sow feeding systems (ESF) often have fewer feeding spaces than traditional individual stall systems, which creates competition for access to feeding spaces (Liu et al., 2021).

---

[1] The material in this chapter was co-authored by Dominique M. Sommer, Jennifer M. Young, Xin Sun, Giancarlo Lopez-Martinez, and Christopher J. Byrd. Each author contributed to the development of the study objectives and experimental design. Dominique M. Sommer had primary responsibility for collecting samples in the field. Dominique M. Sommer was the primary developer of the conclusions that are advanced here. Dominique M. Sommer also drafted and revised all versions of this chapter. All authors served as editors of this chapter.

The process of establishing the social hierarchy involves aggressive interactions that may cause injuries, such as lesions and lameness, as well as poor reproductive performance (Munsterhjelm et al., 2008; Greenwood et al., 2014). The aggressive interactions among sows and gilts in group housing systems can lessen over time. However, an individual sow ranked lower in the hierarchy may have limited access to feeder space throughout the entire gestation period due to higher ranked sows' dominance over the feeder (Bench et al., 2013). This leads to unconsumed rations which can cause poor body condition, performance, and welfare outcomes (Spoolder et al., 2009; Verdon et al., 2015; Maes et al., 2016).

Currently, determining the social hierarchy in group housed breeding females is time-and-labor intensive. However, the ability to quickly identify sows and gilts in the social hierarchy could be beneficial to producers for mitigating any associated poor welfare outcomes. One potential option for overcoming this challenge is to introduce the use of precision livestock farming (PLF) technologies, which have become useful for monitoring health and animal welfare in livestock management (Brown-Brandl et al., 2013; Vargovic et al., 2021). Infrared thermal imaging and radio frequency identification (RFID) feeding system technology are capable of providing real time monitoring of commercially kept livestock (Halachmi and Guarino, 2016). Additionally, with the future development of automated heart rate imaging technologies (Pai et al., 2021; Wang et al., 2021), heart rate and heart rate variability (HRV) measures may be useful for identifying the impact of social stress on swine (De Jong et al., 2000; Marchant-Forde et al., 2004).

A combination of currently available and future PLF technologies could be beneficial animal welfare management tools for producers who utilize group gestation housing systems. The ability to utilize precision technologies to identify group-housed sows within the social hierarchy could benefit producers in managing their breeding herd, and improving sow welfare, and performance. Therefore, the objective of this study was to investigate the use of IRT characteristics, feeding activity obtained from an automated RFID feeding system, and HRV for detecting the social hierarchy within group housed sows. Additionally, we determined the relationship between observed social hierarchy, body condition score (BCS), backfat depth (BF), and reproductive performance.

2.2. Materials and Methods

2.2.1. Animal Care and Use Statement

All procedures and methods performed in this study were approved and carried out in accordance with the North Dakota State University Institutional Animal Care and Use Committee (IACUC #A21044).

2.2.2. Animals and Housing

Thirteen Yorkshire and 36 Yorkshire-crossbred sows with previous experience in group gestation housing were utilized in this study. Five repetitions (n = 14, n = 12, n = 15, n = 15, n = 17) of the study were performed over a 12-month period between May 2021 and May 2022. Seventeen sows were observed in two repetitions. All sows were 12-36 months of age and ranged from 1-7 parities.

Three group gestation pens measuring approximately 7.30 x 7.62 m (Big Dutchman, Holland, MI, USA) were used. Each of the pens were partially slatted and included a protecting wall or a “T” configuration that created two resting areas (each measuring an average of 2.30 x 2.24 m) and a larger communal area. The communal area included two electronic sow feeders (ESF; Big Dutchman, Holland, MI, USA) equipped with RFID technology and a full body race with a rear gate. Additionally, each pen included three water bowls that provided *ad libitum* water access. The ESF manufacturer's recommendation for group size is 20 sows per feeder. In this study, group size varied between replicates, ranging from 12 to 17, but never exceeding 20 sows per gestation pen. Each sow received 1.81 kg of a lactation diet (see below) on the morning of reintroduction to group gestation housing. After reintroduction, sows could consume up to 1.81 kg of 18% as-fed crude protein gestation feed. Sows were allotted 1.81 kg of the gestation diet daily until they were relocated to individual farrowing stalls on d 104 of gestation.

Three to five days after reintroduction to group gestation pens, sows were estrus or "heat" checked utilizing a combination of nose-to-nose contact with boars located in an adjacent heat detector pen and physical stimulation by a caretaker, which included applying pressure to the back of the sow to assess standing estrus. Sows identified to be in standing heat were artificially inseminated. Sows were pregnancy checked by ultrasound (Xinda 8300 Veterinary Ultrasound Scanner, Medical Device Co., Ltd., Zhangjing, Wuxi, China) approximately 35 d after breeding and remained in group gestation pens throughout the entire gestation period.

On d 105 of gestation, sows were moved to individual farrowing stalls (1.83 m x 0.74 m; Big Dutchman, Holland, MI, USA) in a separate farrowing room within the facility. Once in farrowing stalls, sows were given 1.36 kg of an 11% as-fed crude protein lactation diet twice daily until farrowing. After the competition of farrowing, sows were fed to appetite with rations increasing by 0.91 kg each day until the total ration equaled a maximum of 7.26 kg per day. Sows and litters remained together in farrowing stalls for approximately 18 d. Following the lactation period, piglets were weaned from sows and relocated to a separate nursery room. Once piglets were weaned, sows were reintroduced to group gestation housing. Gestation groups consisted of sows who were previously acquainted and parity-one sows that were housed in a pen consisting of gilts prior to their relocation to farrowing stalls.

2.2.3. Behavioral Observation

Behavioral observation occurred upon reintroduction to group gestation housing (experimental procedure d 1), until d 4 of the study. Four video cameras (Lorex LBV2531U Security Cameras, Lorex Technology Inc., Markham, Canada) were installed above each pen to ensure full coverage of the group gestation pen, including the resting areas, the side of the pen with ESF, and above the opposite side of the pen angled toward the ESF. Recordings were transmitted and stored on a digital video recorder (Lorex D441A6B-Z DVR, Lorex Technology Inc., Markham, Canada). After video collection, all video recordings were saved to an external hard drive, merged together, and converted to MP4 format (VideoProc, Digiarty Software Inc., hengdu, Sichuan Province, China) for behavioral coding (The Observer XT 15; Noldus Information Technology, Wageningen, Netherlands).

2.2.3.1. Social hierarchy determination

Twelve hours of video recordings (experimental d 1-2; beginning as sows entered group gestation housing) were used to determine the social hierarchy within groups. This length of time was chosen based on a preliminary observational study, where pen social hierarchy structure was largely unchanged between 12, 24, and 36 h. A single observer collected all behavioral data using a continuous recording rule to document the results of agonistic, or combative, interactions between pen mates during the 12-h observation period. These data were used to calculate the relative dominance index (DI; see description below) of each sow to determine the social hierarchy within groups.

An agonistic interaction was defined as a fight or displacement with physical contact initiated by one individual that included aggressive behavior followed by any submissive behavior performed by either individual involved in the encounter (Langbein and Puppe, 2004).

A previously developed ethogram of social interactions between group housed sows (Jensen, 1980) was used to categorize aggressive and submissive behaviors performed during agonistic interactions. Parallel pressing, inverse parallel pressing, head-to-head knock, head-to-body knock, levering, biting, and physical displacement were considered aggressive behaviors. Retreating during a fight, turning away from an attack, attempting to flee, or displacement from a location were considered submissive behaviors (Jensen, 1980). During an agonistic interaction, the animal that performed a submissive behavior was considered to be 'defeated' while the other individual was considered the 'winner' of the interaction.

In order to calculate the relative social rank of each sow within each group, a DI was calculated using the number of wins and defeats for each sow (Bowen and Brooks, 1978; Stukenborg et al., 2011). To calculate the DI, the following equation was used:

$$\mathrm{DI} = \frac{(\text{wins} - \text{defeats})}{(\text{wins} + \text{defeats})}$$

Dominance index values were used to rank sows from the highest (most dominant) to lowest (least dominant) with a DI closest to 1.00 indicating the most dominant sow and a DI closest to -1.00 indicating the most submissive or lowest ranking sow within the pen. Individuals within groups were then categorized into four rank quartiles (RQ) based on DI, where the first quartile (RQ1) represented the highest-ranked sows with the greatest DI and the fourth RQ (RQ4) represented the lowest-ranked sows (Table 1). These social rank quartiles served as the "Gold Standard" to which precision technologies results were compared.

Table 1. Number of sows allocated to each rank quartile (RQ) per replication (1-5) of the study based on social rank determined by dominance index value (DI). Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked.

	Repetition 1	**Repetition 2**	**Repetition 3**	**Repetition 4**	**Repetition 5**
RQ 1	3	3	4	4	4
RQ 2	4	3	4	4	4
RQ 3	4	4	4	4	5
RQ 4	3	2	3	3	4
Total	14	12	15	15	17

2.2.4. Infrared Thermal Imaging

Infrared thermal images were captured on d 3 of the experimental period and every 15 days after reintroduction to group gestation housing using an infrared thermal imaging camera (FLIR E8, FLIR Systems LLC, Wilsonville, OR). Thermal images were captured behind the neck at the base of the left ear (Fig. 1) between 0700 and 1000h when sows were awake and standing. The base of the ear is an anatomical location previously reported to be reliable for observing body surface temperature changes in swine (Rocha et al., 2019; Farrar et al., 2020) and therefore, was considered the region of interest (ROI) in this study. Measurement parameters, such as emissivity and distance from subject, were set and remained constant throughout the experiment. Emissivity was set to 0.98 (Soerensen et al., 2014) and the distance from subject being captured remained at 1 m. Atmospheric temperature and relative humidity within the gestation pens were collected by data loggers (HOBO Temperature/Relative Humidity Data Logger, Onset Computer Corporation, Bourne, MA). Infrared thermal imaging camera parameter settings related to temperature and humidity were adjusted accordingly throughout the experiment. After IRT collection, images were downloaded and analyzed using an infrared imaging processing software (FLIR Thermal Studio FLIR Systems LLC, Wilsonville, OR). An ellipse was fit to the ROI to identify the maximum (MaxT), mean (MeanT), and minimum (MinT) temperature for each thermal image taken on d 3, d 15, d 30, d 45, d 60, d 75, d 90, and d 105 of the experiment.

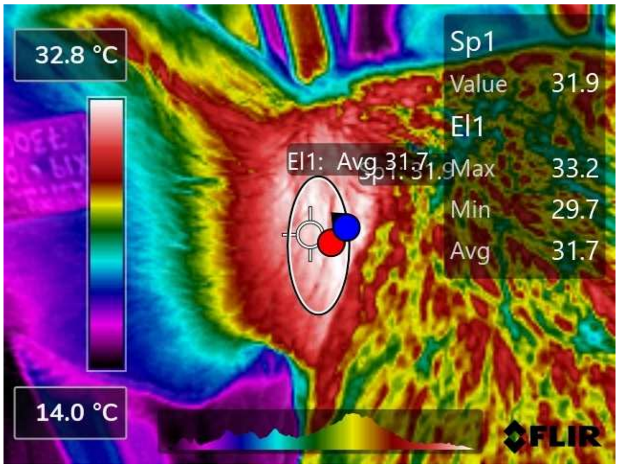

Figure 1. Infrared thermogram of behind the neck at the base of the left ear, or region of interest (ROI), of a sow housed in group gestation housing.

2.2.5. Feed Data

Sow identification ear tags equipped with RFID transponders were used to identify each sow using the ESF system (Big Dutchman, Holland, MI, USA) within group gestation. The ESF contained an antenna at the front that read the RFID transponder and feed was distributed in the back left corner of the feed trough to encourage sows to place their right ear near the antenna. The ESF dispensed feed until sows exited the feeder or until the daily allotted ration was dispensed. Various feed data were collected automatically by the ESF system. The time at entrance and exit of the feeder was recorded. Additionally, the amount of feed distributed during a visit was recorded, which allowed the software program to calculate total feed offered for the day and the remaining feed in each sow's individual daily allotment. The amount of feed distributed is based on a calibration of how much feed is dispensed during one revolution of the auger. Therefore, only feed offered and not feed consumed can be evaluated. Daily feed allotments were for 0000 to 2359. Feeding behavior was documented beginning on d 1 of the experimental procedure until approximately d 105 of gestation. Feed data were exported from the ESF system and used to calculate various feeding behavior traits (Table 2). Due to technical difficulties with the ESF system during the fourth and fifth repetitions of the study, portions of data were removed from the data set due to feeder failure to dispense feed (14 d worth of data were removed for repetitions 4 and 5). Additionally, the software program for the ESF failed to save the first month of data for the first repetition (40 d total were lost).

2.2.5.1. Feeding Behavior Traits

Feeding behavior traits were calculated using data generated from the ESF and are defined in Table 2. Due to the ESF system recording any time the sow's right ear moved away from the antenna as separate visits, even if she did not leave the feeding space (*i.e.,* eating from the right side of the trough instead of the left), feed data from a non-project sow was plotted to look for an obvious break in times between visits and meals (Tolkamp et al., 2011). As a result, ESF visits, which occurred with less than a 55 s break between end time of the first visit and start time of the next visit were combined and defined as one visit, while a threshold of 5 m (300 s) was used to define one meal. For each sow, combined feeding events were then used to construct feeding behavior traits per day, meal, and visit (Table 2). Because sows could enter the feeder even after they consumed their daily allotment, feeing behavior traits were also evaluated for visits/meals with feed offered and visits/meals with no feed offered. Additionally, feeding behavior traits were also calculated per hour over a 24-hour period, with h 0 representing 0000-0059 and h 24 representing 2300-2359.

Table 2. Feeding behavior trait definitions calculated for each sow.

Feeding behavior trait	Definition
Feed offered	The amount of feed (kg) offered to a sow during a duration of time within the electronic sow feeder (ESF)
Occupation time	The amount of time (s) a sow remained within the ESF continuously
Number of visits	The number of times (count) a sow entered the ESF per day or per hour
Number of meals	The number of times (count) a sow entered the ESF and remained within the feeder per day or per hour
With feed	Refers to visits or meals in which a sow remained within the ESF and feed was dispensed into feed trough
Without feed	Refers to visits or meals in which a sow remained within the ESF but feed was not dispensed into feed trough

2.2.6. Heart Rate Variability

One week prior to relocation to group gestation housing, all sows in farrowing stalls were acclimated to wearing a telemetric heart rate (HR) monitor (Polar H10 Heart Rate Sensor, Polar Electro, Kempele, Finland) for 30 min per day for 3 d while remaining in individual farrowing crates. Heart rate monitor straps were placed around the sows' chest, behind the front legs, with electrodes over the left side of the chest, and the monitor placed behind the elbow. Electrode gel (Spectra 360 Electrode Gel, Parker Laboratories Inc., Fairfield, NJ) was applied to the HR monitor straps prior to strap placement to better facilitate contact between skin and electrodes during data collections.

After the acclimation period, 10 randomly selected sows within each farrowing group (n = 50; 10 per replicate) were chosen for HR data collection. One day before sows were moved from farrowing to gestation housing (d 0), HR straps and monitors were fit around the chest of each sow. Flexible bandage wrap (VetWrap; 3M, Maplewood, MN) was used to secure the HR straps in place to prevent movement of electrodes. Sixty minutes of instantaneous, continuous HR data from each selected sow were collected (baseline data) and transmitted via Bluetooth to an individual iPod Touch (Apple Inc., Cupertino, CA) using the Elite HRV application (Elite

HRV, Asheville, North Carolina). The following day (d 1), the HR data collection procedure was repeated for each sow as they were reintroduced to gestation penning (post-mixing data). After 240 min of HR data collection, the HR monitors and straps were removed.

Collected HR data were exported, reviewed, and errors were edited manually using previously determined methods for artifact correction (Marchant-Forde et al., 2004). No data set used for analysis had more than 5% corrected errors. Data with more than five consecutive heartbeat interval errors were not used. Three hundred seconds of continuous times between adjacent heart beats (RR intervals) were collected during periods of sow inactivity on d 0 and d 1 were used to calculate linear HRV measures using a freely available HRV software package (Kubios HRV Standard, Kubios Oy, Kuopio, Finland). The following HRV measures, and their definitions, collected for this experiment were: 1) average RR interval (ms), defined as the average interval between adjacent heat beats over a period of time, 2) the standard deviation of RR intervals (SDNN; ms) defined as the standard deviation of all RR intervals over a period of time, and 3) the root mean square of successive differences (RMSSD; ms) defined as the root mean square of successive RR intervals over a period of time (Byrd, 2018).

2.2.7. Liveweight Measurements

One week prior to reintroduction to group gestation housing, baseline BCS as well as BF, measured at the 10th rib via ultrasound (Xinda 8300 Veterinary Ultrasound Scanner, Medical Device Co., Ltd., Zhangjing, Wuxi, China), were documented for each sow. Body condition scores on a 3- and 6-point scale (BCS3 and BCS6, respectively) were measured for each sow using a sow body condition caliper tool (Knauer and Baitinger, 2015). A BCS3 value of 1 indicates a thin sow, a value of 2 indicates an ideal conditioned sow, while a BCS3 value of 3 indicates an overweight sow. A BCS6 value of 1 indicates an extremely thin sow, a value of 2 or

3 indicates an ideal conditioned sow, and a BCS6 value of 4, 5, or 6 indicates an overweight sow. Throughout the study, BCS3, BCS6, and back fat depth (BF) of each sow was measured every 15 days after reintroduction to the group gestation housing (d 15, d 30, d 45, d 60, d 75, d 90, and d 105).

2.2.8. Reproductive Performance

At approximately 105 d of gestation, sows were relocated from group gestation housing to individual farrowing stalls. After the completion of farrowing, all fully formed piglets were identified and weighed. The number of mummies was also recorded. From this data: the number of piglets born alive, number of piglets dead at birth, number of mummies, total number of piglets farrowed, farrowing survival (number born alive as a percentage of total number born), number of piglets born less than 1 kg, and total litter birth weight (kg) were calculated. During the suckling period, any piglets which died were identified and the cause of death was recorded. From this data, the number of piglets that died due to failure to thrive were calculated. At 18-21 days of age, piglets were weighed, vaccinated, and relocated to the nursery. From this data, the number weaned, preweaning survival (number weaned as a percentage of number born alive), total litter weaning weight (kg), and the number of piglets with adjusted weaning weights to 18 d of age of less than 4.54 kg, also referred to as light weight at weaning, were calculated.

2.2.9. Statistical Analysis

Data were analyzed in SAS (v. 9.4; SAS Institute, Inc., Cary, NC). Correlations of DI with reproductive and feeding behavior traits were estimated using the CORR procedure in SAS.

Thermal imaging characteristics (MaxT, MeanT, and MinT) were analyzed using thE MIXED procedure. Backfat depth was fit as a covariate and repetition as a random effect. Fixed effects included were day, RQ, and their interaction. A repeated measures statement with sow nested with repetition was fitted to account for the multiple day measurements. Feeding behavior traits were analyzed using the mixed procedure. For non-hourly traits, age was included as a covariate, RQ as a fixed effect, and repetition as a random effect. Due to the fact some sows were repeated between different repetitions, sow was also fit as a random effect. A repeated measures statement was not used because not all sows were repeated, and using a repeated measures statement caused issues with model convergence. For hourly feeding behavior traits, the same model was used and added hour and the interaction of hour and RQ as fixed effects. For baseline HRV traits, the mixed procedure was used, fitting RQ as a fixed effect, age as a covariate, and sow and repetition as random effects. For reintroduction HRV traits, their respective baseline measurement was used as a covariate (*i.e.,* baseline SDNN for reintroduction SDNN). Because BCS3 and BCS6 are categorical in nature, data were analyzed using the glimmix procedure. Day, RQ, and their interaction were fit as fixed effects while sow and repetition were fit as random effects. Backfat depth was analyzed using the mixed procedure, fitting day, RQ, and their interaction as fixed effects and repetition as a random effect. A repeated measures statement with sow as the subject was fit to account for the multiple day measurements.

For reproductive traits, both the GLIMMIX and MIXXED procedures were utilized. Number born alive, number dead at birth, number of mummies, total number farrowed, and number of piglets less than 1 kg at birth were analyzed using the GLIMMIX procedure, fitting RQ as a fixed effect, parity and gestation length as covariates, and sow and repetition as random effects. Farrowing survival was analyzed using the mixed procedure, fitting RQ as a fixed effect, parity and gestation length as covariates, and sow and repetition as random effects. For total litter birth weight, the mixed procedure was used fitting RQ as a fixed effect, parity and gestation length as covariates, and sow, boar (piglet's sire), and repetition as random effects. Number of failure to thrives, number weaned, and number less than 4.5 kg adjusted weaning weight were analyzed using the glimmix procedure, fitting RQ as a fixed effect, parity as a covariate, and sow and repetition as random effects. Pre-weaning survival was analyzed using the mixed procedure, fitting RQ as a fixed effect, parity as a covariate, and sow and repetition as random effects. Total litter weaning weight was analyzed using the mixed procedure, fitting RQ as a fixed effect, parity and lactation length as covariates, and sow, boar, and repetition as random effects.

For all repeated measures statements, different covariance structures were evaluated and the covariate structure resulting in the lowest AICC score was selected for use. The least squares means statement with the DIFF option was used to determine differences between RQ and interactions (*i.e.,* day or hour) with RQ for all traits.

2.3. Results

2.3.1. Thermal Imaging

No differences were found between RQ for any thermal imaging characteristics throughout the experiment ($P > 0.05$; Table 3). A day effect was found for all thermal imaging characteristics ($P < 0.0001$), with MeanT steadily decreasing throughout the experimental period (Fig. 2). The remaining imaging characteristics (MinT and MaxT) followed a similar pattern (data not shown). Backfat depth influenced MinT ($P = 0.04$; data not shown) but had no effect on MeanT or MaxT ($P > 0.05$).

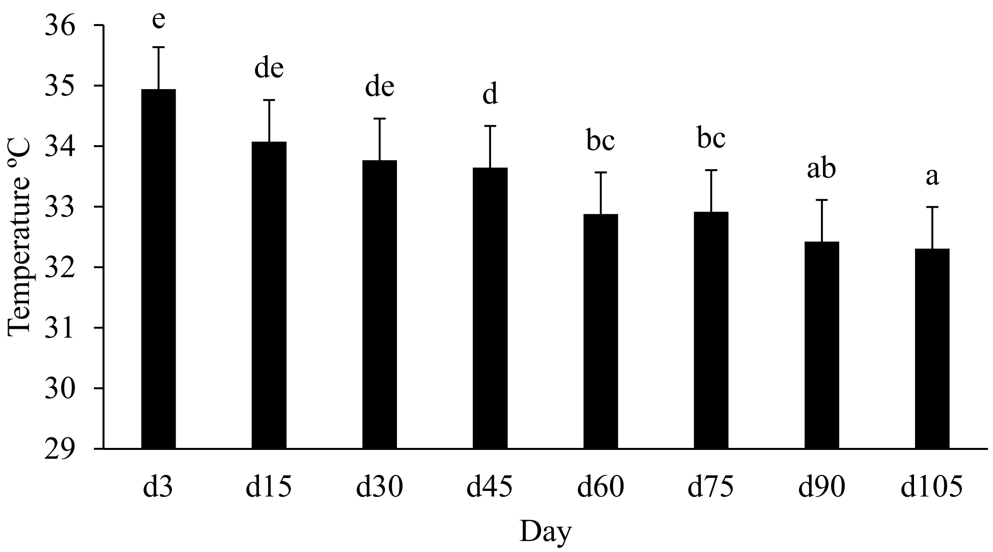

Figure 2. Mean thermal image temperature (MeanT) organized by experimental day (3, 15, 30, 45, 60., 75, 90, 105) (LS means ± SE). Different superscripts indicate differences ($P < 0.05$) between experimental days.

Table 3. Mean (MeanT), maximum (MaxT), and minimum (MinT) thermal image temperatures (LS means ± SE) organized by rank quartile (RQ). Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked.

Thermal Image Characteristic	**RQ 1**	**RQ 2**	**RQ 3**	**RQ 4**	***P - value***
MaxT	34.4 ± 0.6	34.7 ± 0.6	34.7 ± 0.6	34.7 ± 0.6	*0.25*
MeanT	33.2 ± 0.7	33.4 ± 0.7	33.4 ± 0.7	33.4 ± 0.7	*0.61*
MinT	31.4 ± 0.8	31.5 ± 0.8	31.6 ± 0.8	31.6 ± 0.8	*0.41*

2.3.2. Feeding Behavior Traits

Feeding behavior traits and their association with RQ are presented in Table 4. Rank quartile was associated with occupation time per visit (*P* = 0.045). Sows within RQ2 had the greatest occupation time, while RQ4 had the shortest occupation time (Table 4). A similar result was found for occupation time per visit with feed (*P* = 0.01; Table 4) There was also an effect of RQ on the number of visits per day and the number of visits per day with feed (*P* = 0.01 and *P* = 0.02, respectively), where RQ4 had the greatest number of visits per day (Table 4). No other differences were found for the remaining feeding behavior traits. However, RQ tended (*P* = 0.08) to influence feed offered per visit with feed (Table 4).

Table 4. Feeding behavior traits (LS means ± SE) organized by rank quartile (RQ). Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked. Different superscripts indicate differences ($P < 0.05$) between RQ for each feeding behavior trait.

Feeding Behavior Trait		**RQ 1**	**RQ 2**	**RQ 3**	**RQ 4**	***P - value***
Feed offered (kg)	*Per visit*	0.71 ± 0.12	0.71 ± 0.12	0.56 ± 0.12	0.51 ± 0.12	*0.20*
	Per meal	0.96 ± 0.13	0.87 ± 0.12	0.77 ± 0.13	0.84 ± 0.13	*0.47*
	Per visit with feed	1.11 ± 0.09	1.6 ± 0.08	.93 ± 0.09	0.86 ± 0.09	*0.08*
	Per meal with feed	1.38 ± 0.07	1.4 ± 0.06	1.3 ± 0.07	1.32 ± 0.08	*0.70*
Occupation time (s)	*Per visit*	281. 94 ± 30.80^{bc}	296.40 ± 29.05^{c}	239. 39 ± 30.50^{ab}	212.19 ± 31.49^{a}	***0.0451***
	Per meal	464.10 ± 36.15	437.08 ± 33.34	396.31 ± 35.60	434.13 ± 37.32	*0.48*
	Per day	909.29 ± 140.0	1072.51 ± 130.10	1154.55 ± 138.90	1087.95 ± 143.36	*0.33*
	Per visit with feed	361.80 ± 30.23^{bc}	393.70 ± 26.90^{c}	303.16 ± 29.0^{ab}	254.96 ±31.40^{a}	***0.0124***
	Per meal with feed	586.70 ± 49.48	604.22 ± 46.03	538.39 ± 49.0	520.23 ± 50.93	*0.43*
	Per visit without feed	169.57 ± 25.18	182.74 ± 22.30	160.13 ± 24.0	181.0 ± 25.54	*0.81*
	Per meal without feed	195.0 ± 34.02	222.05 ± 29.84	180.72 ± 32.17	233.20 ± 34.55	*0.50*
	Per day without feed	486.65 ± 150.69	591.63 ± 128.62	784.55 ± 141.14	714.55 ± 157.40	*0.57*
Number of visits	*Per day*	4.48 ± 1.05^{a}	4.67 ± 0.98^{a}	7.0 ± 1.04^{b}	8.05 ± 1.08^{b}	***0.0149***
	Per day with feed	2.74 ± 0.79^{ab}	2.61 ± 0.71^{a}	4.14 ± 0.78^{abc}	5.78 ± 0.82^{c}	***0.0177***
	Per day without feed	2.94 ± 0.63	3.17 ± 0.56	4.21 ± 0.61	3.32 ± 0.70	*0.37*
Number of meals	*Per day*	3.20 ± 0.82	3.39 ± 0.77	4.85 ± 0.81	4.71 ± 0.84	*0.19*
	Per day with feed	1.71 ± 0.41	1.69 ± 0.38	2.30 ± 0.4	2.63 ± 0.43	*0.29*
	Per day without feed	2.61 ± 0.55	2.82 ± 0.5	3.72 ± 0.54	3.06 ± 0.57	*0.34*

2.3.2.1. Hourly Feeding Behavior Traits

All feeding behavior traits per hour over a 24-h period between RQ can be seen in Figures 3, 5, 7, and 9-15. The interaction between RQ and hour was associated with feed offered per hour ($P = 0.003$), where RQ4 sows had the lowest feed offered during hours 0, 1, and 2 and the greatest feed offered per hour during h 8 compared to all other RQ (Fig. 4). Occupation time per hour and occupation time per hour with feed was also influenced by RQ ($P = 0.01$ and $P = 0.0007$, respectively; Figures 6 and 8). No additional differences were found for the remaining hourly feeding behavior traits ($P > 0.05$).

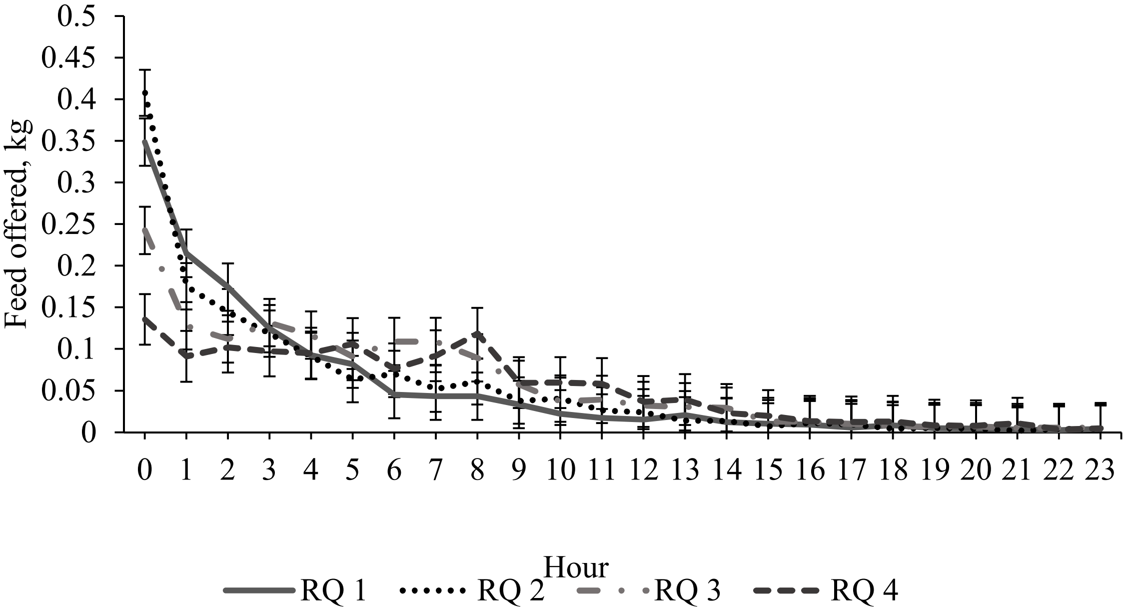

Figure 3. Feed offered per hour (kg) over a 24 h period between rank quartiles (RQ) (LS means ± SE). Hour 0 represents 0000 h. Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked. Overall differences between RQ were not observed ($P > 0.05$).

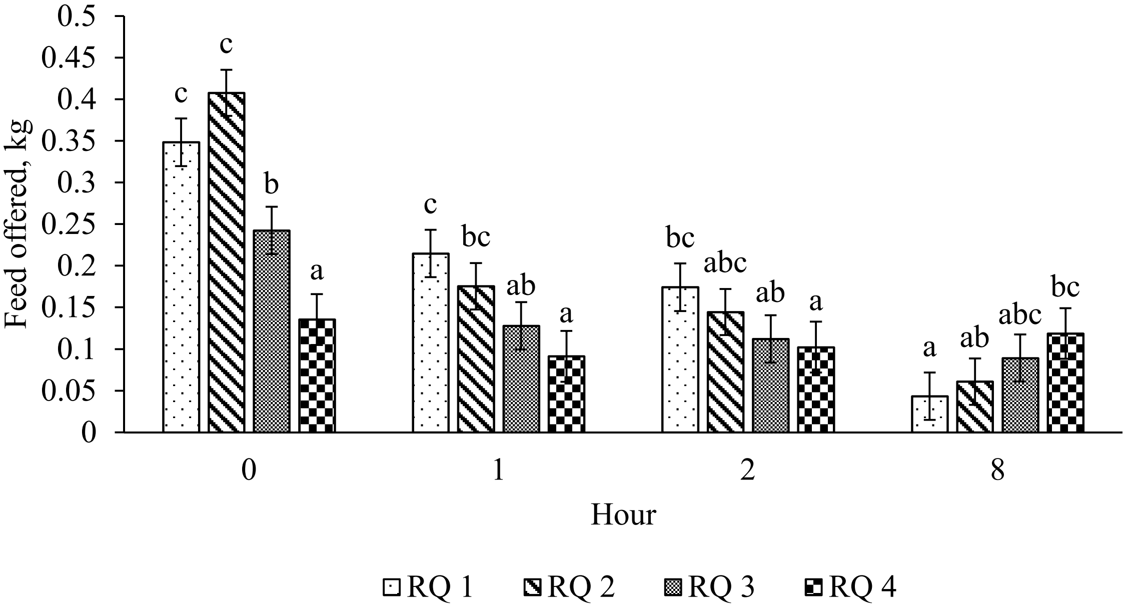

Figure 4. Feed offered (kg) per hour for h 0, 1, 2, and 8 organized by rank quartile (RQ) (LS means ± SE). Hour 0 represents 0000 h. Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked. Different superscripts indicate differences (*P* < 0.05) between RQ for each hour.

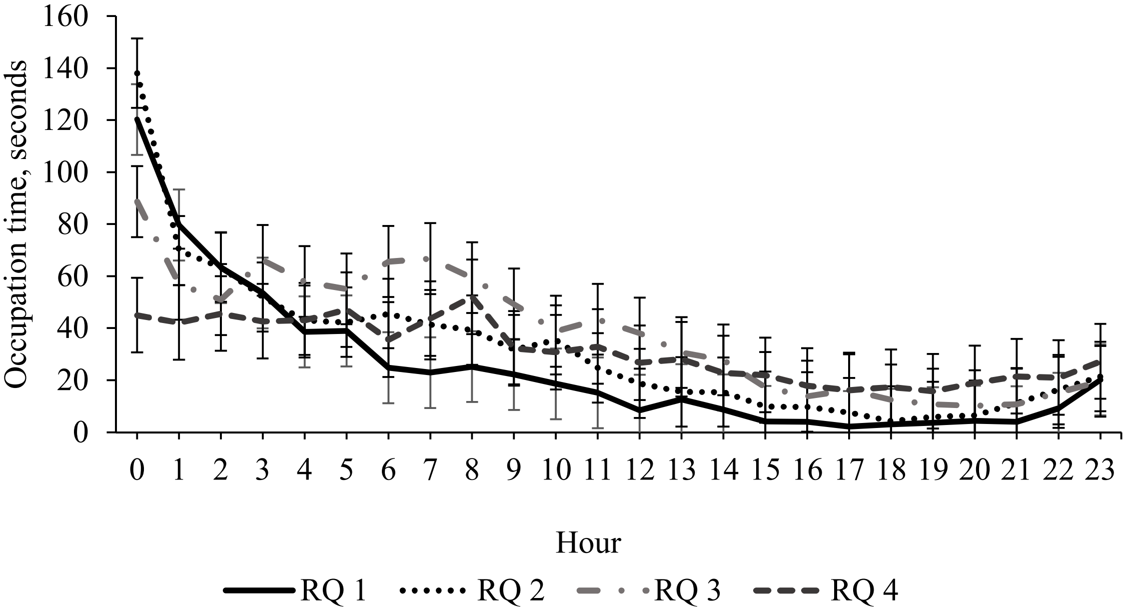

Figure 5. Electronic sow feeder occupation time (seconds) per hour over a 24 h period between rank quartiles (RQ) (LS means ± SE). Hour 0 represents 0000 h. Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked. Overall differences between RQ were not observed (*P* > 0.05).

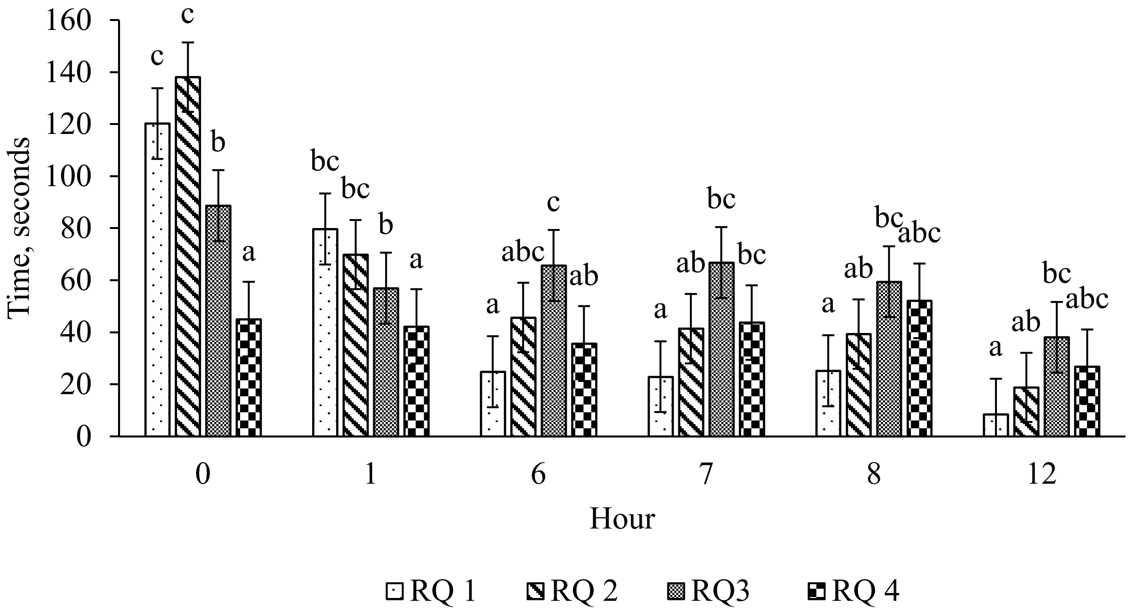

Figure 6. Electronic sow feeder occupation time (seconds) per hour for h 0, 1, 6, 7, 8, and 12 organized by rank quartile (RQ) (LS means ± SE). Hour 0 represents 0000 h. Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked. Different superscripts indicate differences ($P < 0.05$) between RQ for each hour.

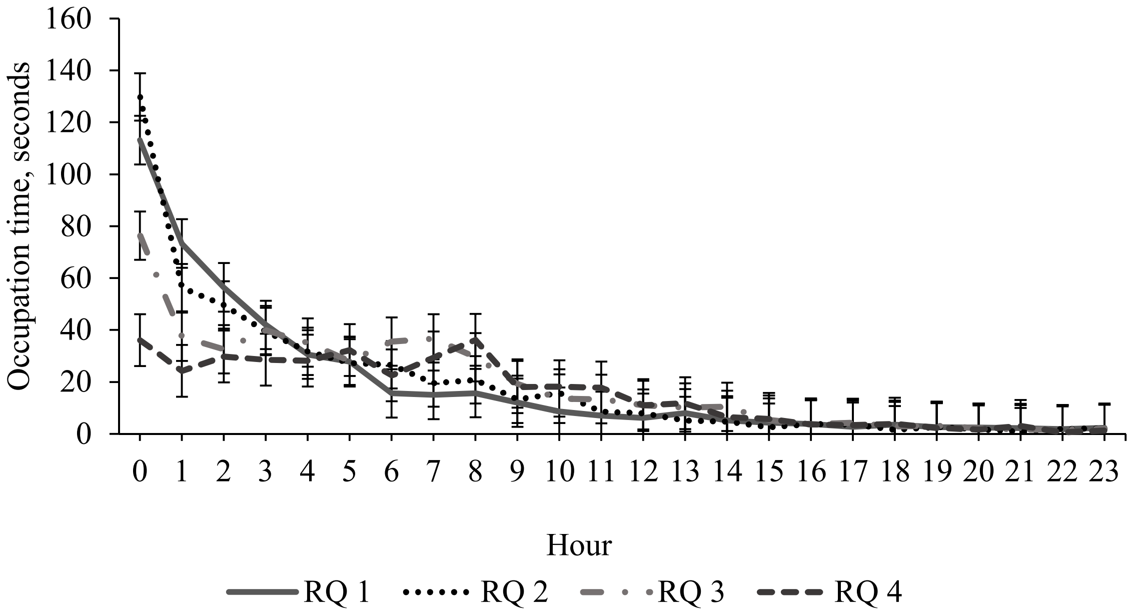

Figure 7. Electronic sow feeder occupation time (seconds) per hour when feed was received over a 24 h period organized by rank quartile (RQ) (LS means ± SE). Hour 0 represents 0000 h. Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked. Overall differences between RQ were not observed ($P > 0.05$).

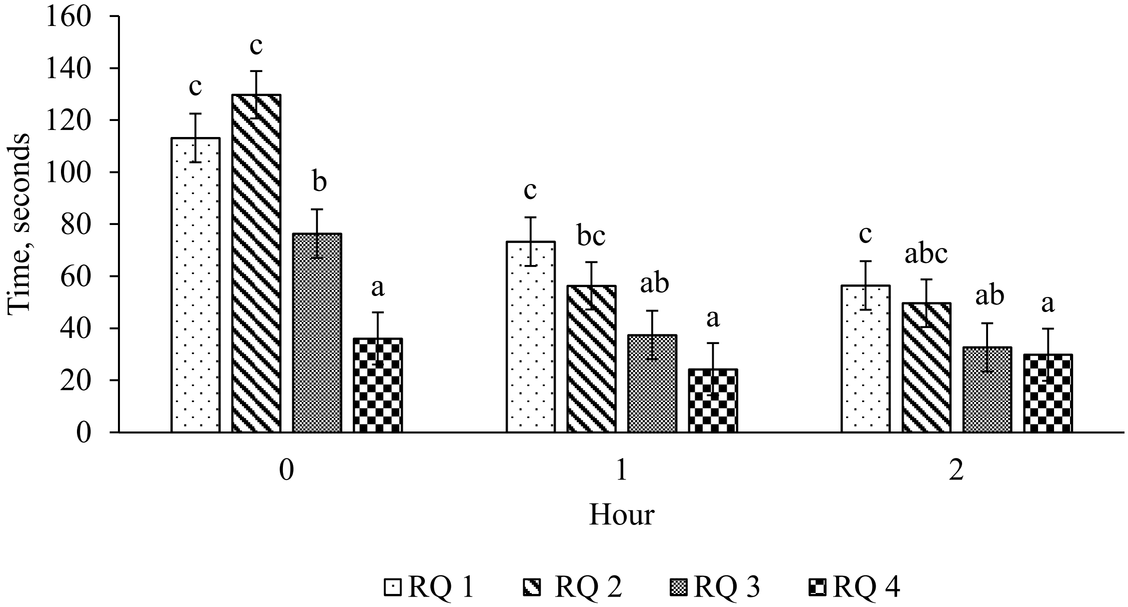

Figure 8. Electronic sow feeder occupation time (seconds) per hour when sows received feed for h 0, 1, and 2 organized by rank quartile (RQ) (LS means ± SE). Hour 0 represents 0000 h. Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked. Different superscripts indicate differences (P < 0.05) between RQ for each hour.

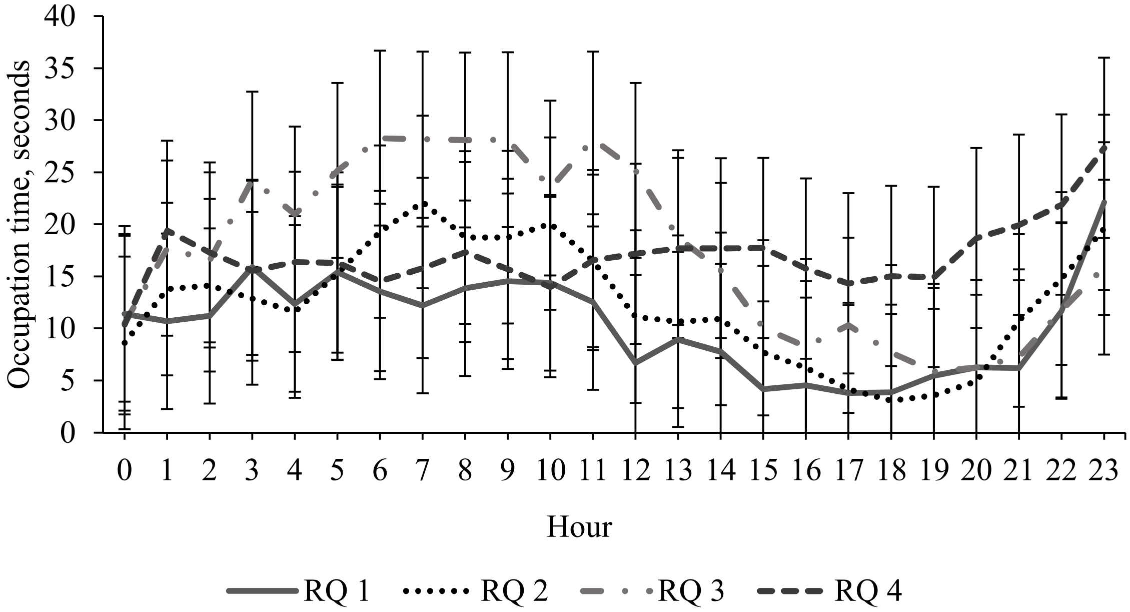

Figure 9. Electronic sow feeder occupation time (seconds) per hour when feed was not received over a 24 h period organized by rank quartile (RQ) (LS means ± SE). Hour 0 represents 0000 h. Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked. Overall differences between RQ were not observed (*P* > 0.05).

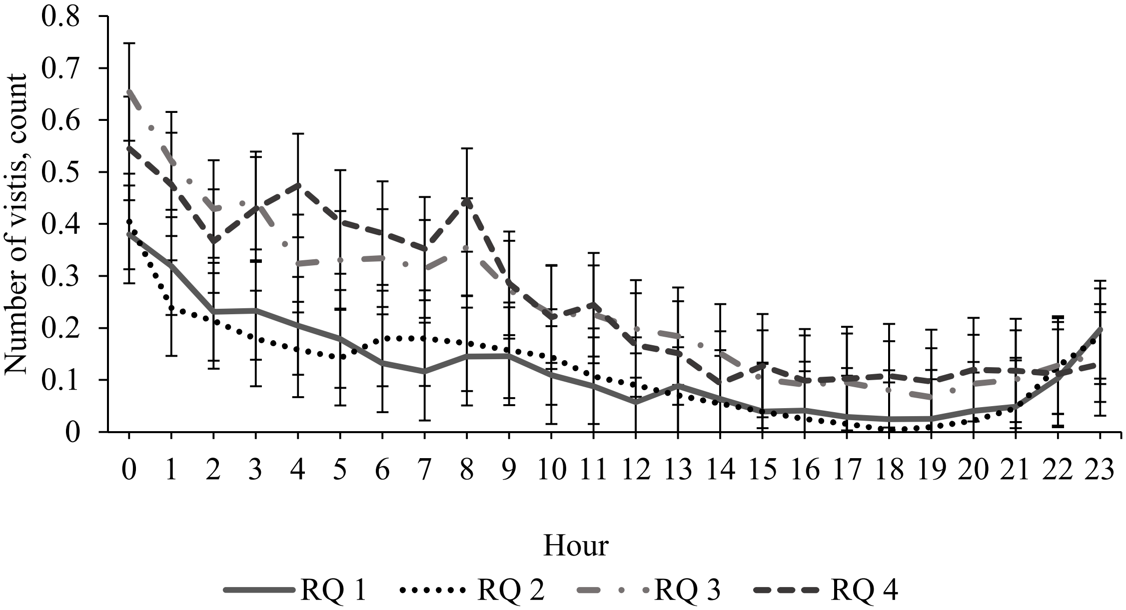

Figure 10. Electronic sow feeder visits (count) per hour over a 24 h period between rank quartiles (RQ) (LS means ± SE). Hour 0 represents 0000 h. Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked. Overall differences between RQ were observed (*P* = 0.0004).

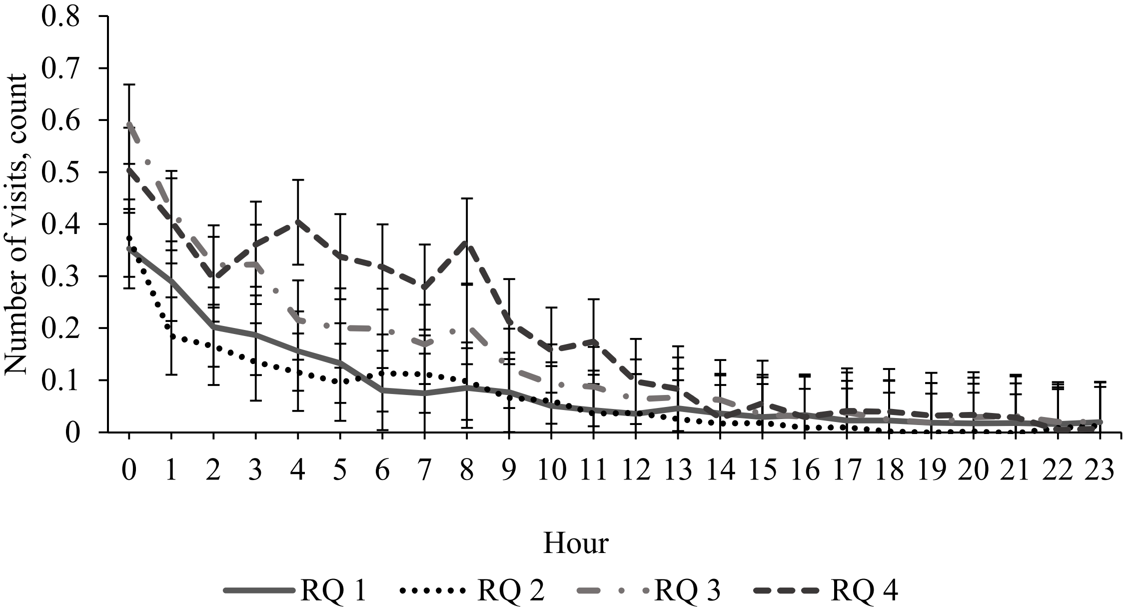

Figure 11. Electronic sow feeder visits per hour where feed was received (count) over a 24 h period organized by rank quartile (RQ) (LS means ± SE). Hour 0 represents 0000 h. Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked. Overall differences between RQ were observed (*P* = 0.0009).

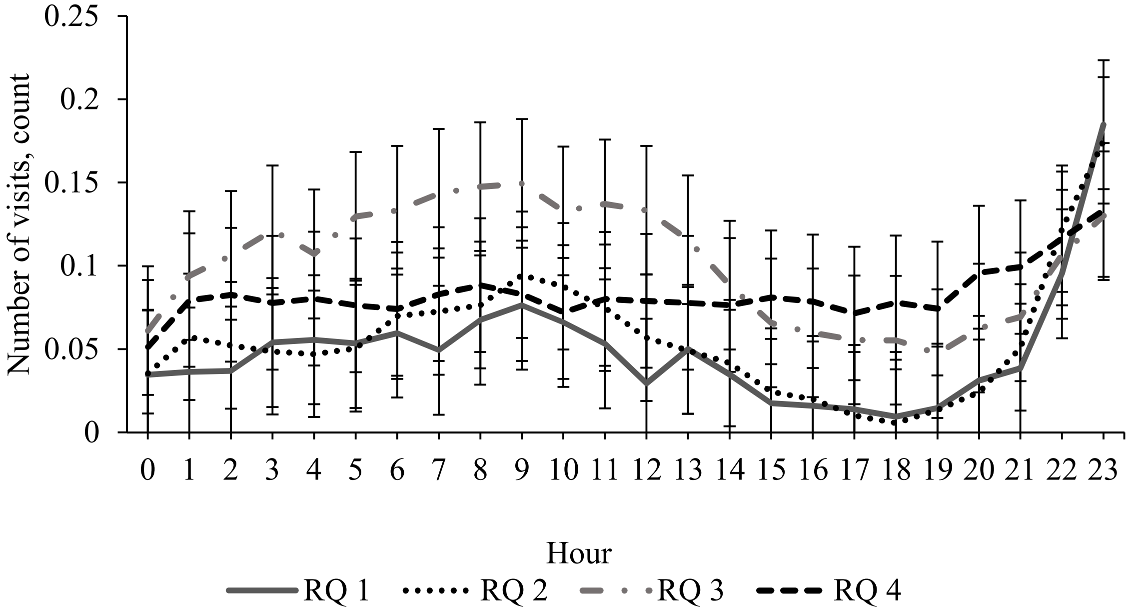

Figure 12. Electronic sow feeder visits per hour where feed was not received (count) over a 24 h period organized by rank quartile (RQ) (LS means ± SE). Hour 0 represents 0000 h. Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked. Overall differences between RQ were observed ($P = 0.003$).

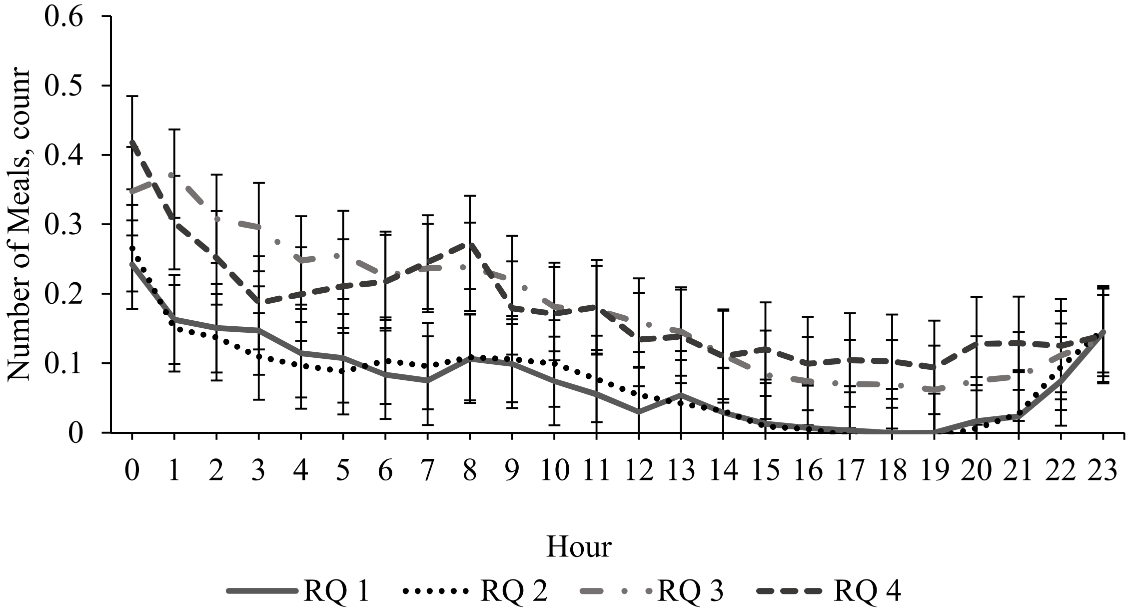

Figure 13. Number of meals (count) per hour over a 24 h period between rank quartiles (RQ) (LS means ± SE). Hour 0 represents 0000 h. Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked. Overall differences between RQ were observed ($P < 0.0001$).

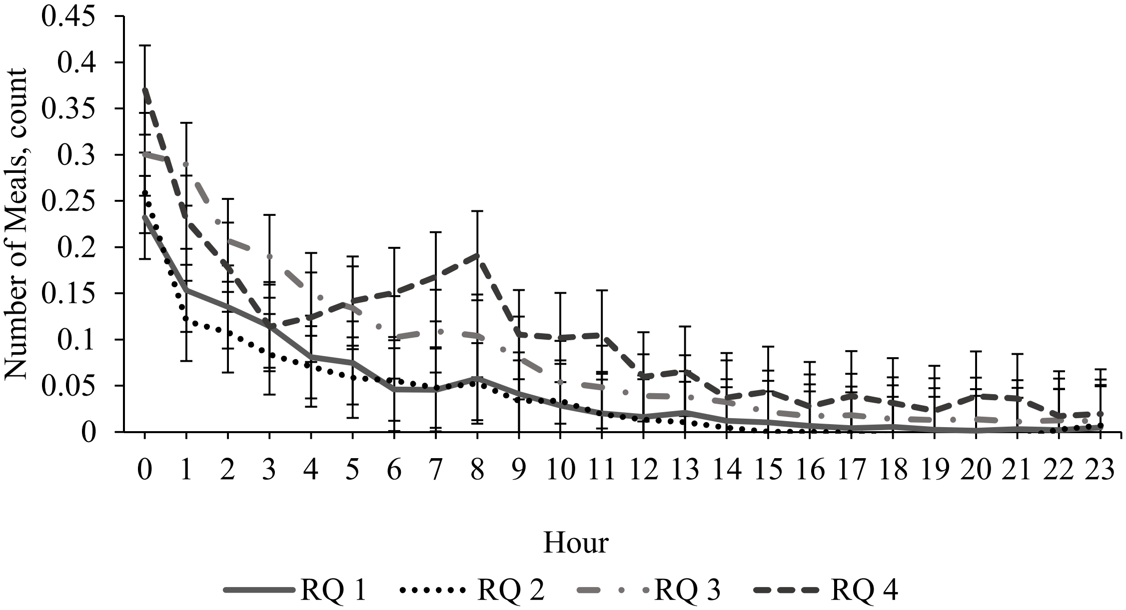

Figure 14. Number of meals per hour where feed was received (count) over a 24 h period organized by rank quartile (RQ) (LS means ± SE). Hour 0 represents 0000 h. Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked. Overall differences between RQ were observed (*P* = 0.004).

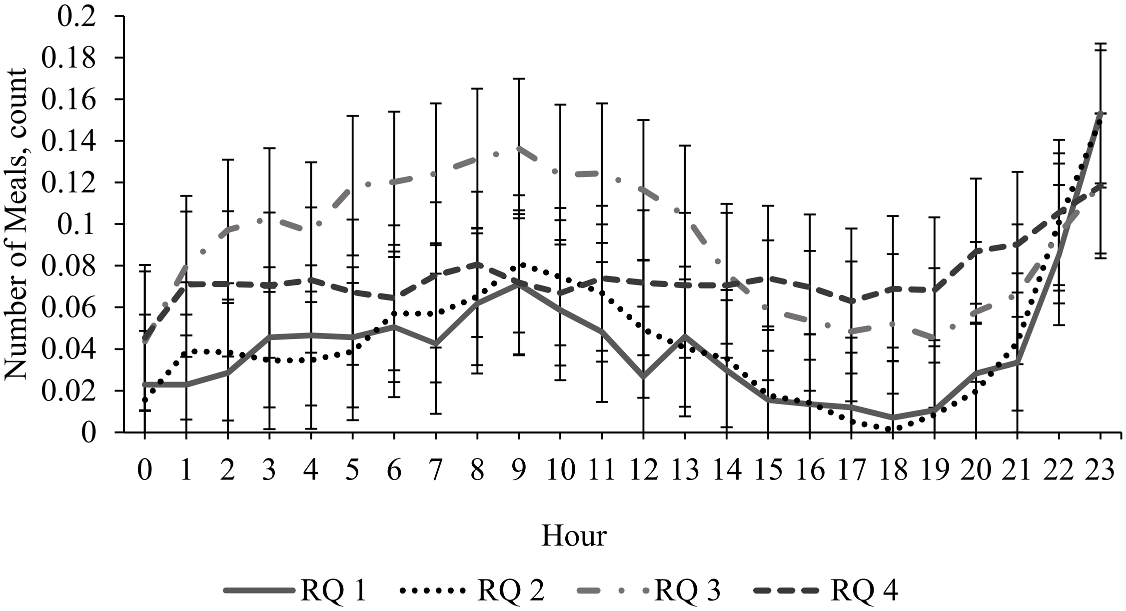

Figure 15. Number of meals per hour where feed was not received (count) over a 24 h period organized by rank quartile (RQ) (LS means ± SE). Hour 0 represents 0000 h. Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked. Overall differences between RQ were observed (*P* = 0.0005).

2.3.3. Heart Rate Variability

Rank quartile was associated with baseline RR interval (*P* < 0.0001; Table 5) and baseline SDNN (*P* = 0.004; Table 5). Rank quartile tended to influence baseline RMSSD (*P* = 0.1; Table 5) with RQ4 exhibiting lower values compared to all other RQ. Rank quartile was not associated with any HRV measures during the post-mixing period (*P* > 0.05; Table 5).

Table 5. Heart rate variability (HRV) measures (LS means ± SE) prior to reintroduction to group gestation housing (Baseline) and after reintroduction (Post-mixing) organized by rank quartile (RQ). Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked. Different superscripts indicate differences (*P* < 0.05) between RQ for each HRV measure.

	Measure	**RQ 1**	**RQ 2**	**RQ 3**	**RQ 4**	***P-value***
Baseline	*RR*	619.56 ± 10.74^{c}	642.32 ± 10.73^{d}	531.58 ± 10.73^{a}	532.11 ± 10.73^{b}	***<0.0001***
	SDNN	11.84 ± 2.08^{ab}	17.90 ± 1.91^{c}	15.41 ± 1.56^{bc}	11.79 ± 1.91^{a}	***0.004***
	RMSSD	9.27 ± 1.40	8.40 ± 1.28	6.60 ± 1.13	5.0 ± 1.30	*0.10*
Post-Mixing	*RR*	526.33 ± 27.3	572.38 ± 33.76	542.24 ± 25.37	527.25 ± 28.8	*0.62*
	SDNN	15.51 ± 4.21	22.45 ± 4.85	15.76 ± 4.2	18.75 ± 4.48	*0.62*
	RMSSD	5.77 ± 3.8	11.44 ± 4.43	8.52 ± 3.89	10.28 ± 4.15	*0.76*

2.3.4. Liveweight Measurements

No differences were found between RQ for BCS3 or BCS6 (*P* > 0.05; Table 6). Day was associated with both BCS3 and BCS6 (*P* < 0.0001; Figures 16-17). Specifically, body condition score decreased for both scoring systems over time. Day also influenced BF (*P* = 0.0004), which increased from baseline (d 0) to d 60 (Fig. 18). However, RQ was not associated with BF (*P* = 0.57; Table 6).

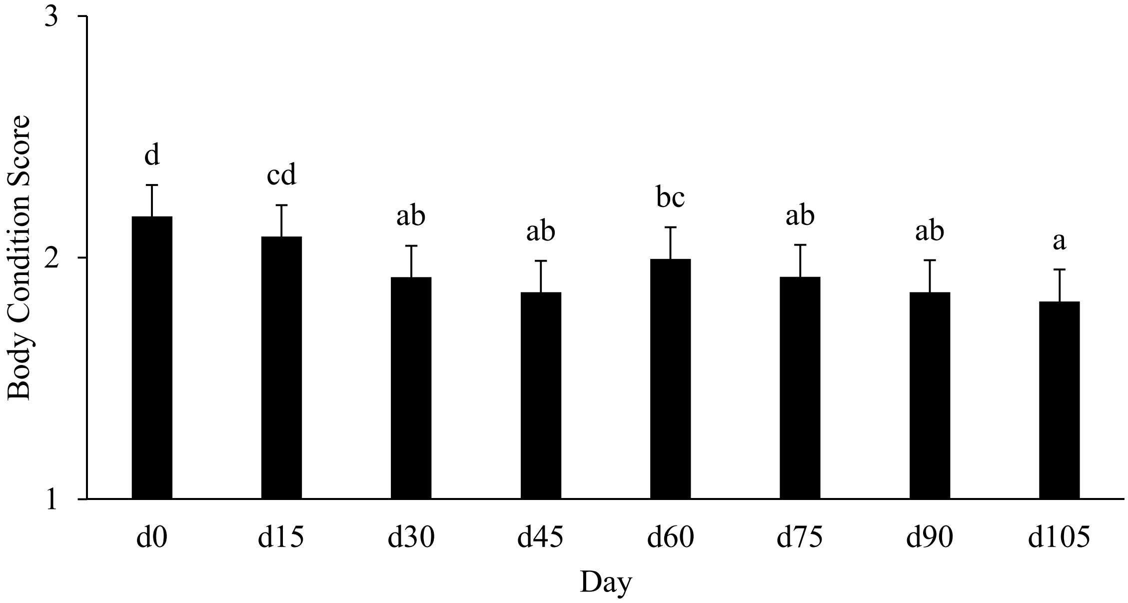

Figure 16. Body condition score on a three-point scale organized by experimental day (0, 15, 30, 45, 60, 75, 90, 105) (LS means ± SE). Different superscripts indicate differences ($P < 0.05$) between experimental days.

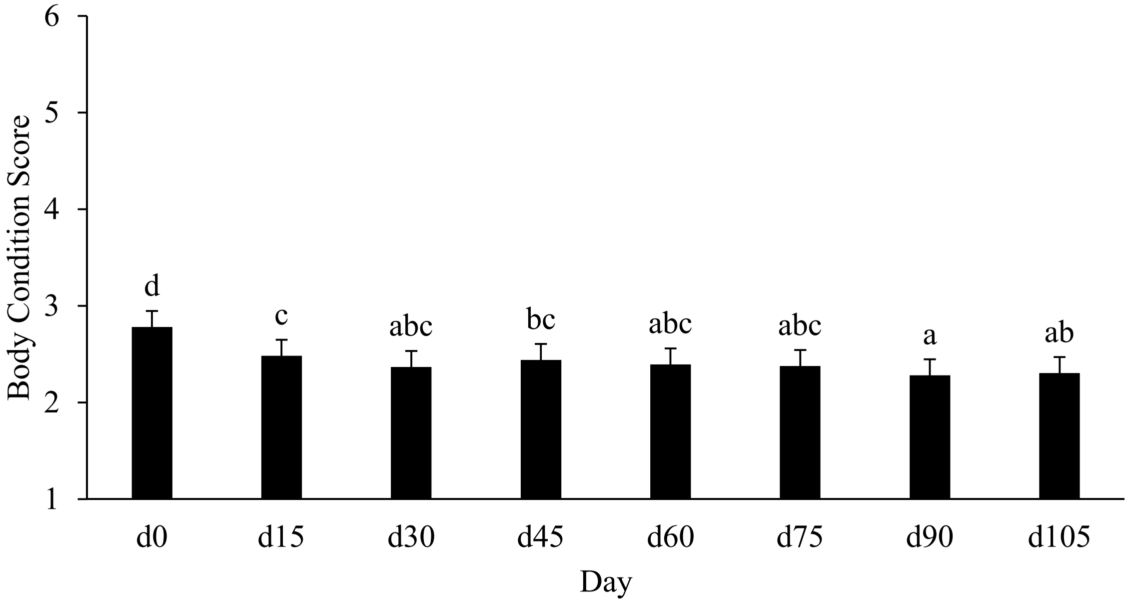

Figure 17. Body condition score on a six-point scale organized by experimental day (0, 15, 30, 45, 60, 75, 90, 105) (LS means ± SE). Different superscripts indicate differences ($P < 0.05$) between experimental days.

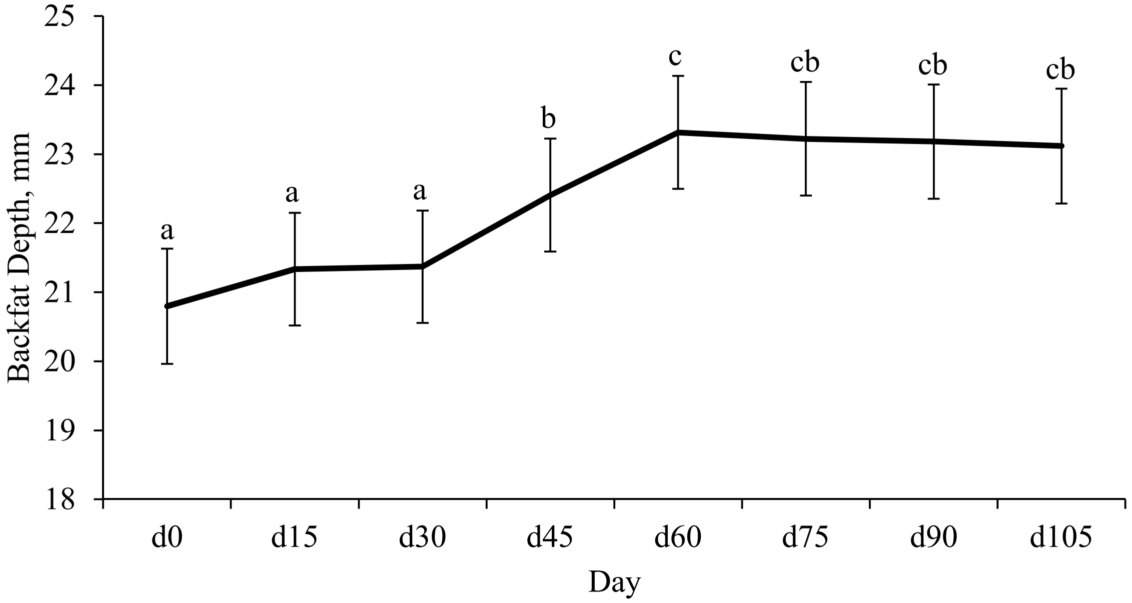

Figure 18. Backfat depth (mm) organized by experimental day (0, 15, 30, 45, 60, 75, 90, 105) (LS means ± SE). Different superscripts indicate differences ($P < 0.05$) between experimental days.

Table 6. Body condition scores on a 3- and 6-point scale (BCS3 and BCS6, respectively) and backfat depth (BF) (LS means ± SE) organized by rank quartile (RQ). Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked.

Trait	**RQ 1**	**RQ 2**	**RQ 3**	**RQ 4**	***P* - value**
BCS3	1.99 ± 0.14	1.91 ± 0.13	2.02 ± 0.13	1.9 ± 0.14	*0.31*
BCS6	2.52 ± 0.17	2.39 ± 0.17	2.43 ± 0.17	2.39 ± 0.17	*0.28*
Backfat depth (mm)	22.66 ± 1.02	21.98 ± 1.01	22.15 ± 1.01	21.78 ± 1.03	*0.91*

2.3.5. Reproductive Performance

Farrowing performance was not affected by RQ ($P > 0.05$; Table 7). However, RQ tended to influence the number of mummies born ($P = 0.08$; Table 7), with RQ4 having a greater number of mummies born per litter than RQ1, RQ2, and RQ 3. No RQ differences were found for any of the weaning performance traits that were evaluated ($P > 0.05$).

Table 7. Farrowing and weaning performance measures (LS means ± SE) organized by rank quartile (RQ). Rank quartile 1 sows ranked highest in the social hierarchy while sows within RQ4 were the lowest ranked sows. Rank quartile 2 and RQ3 sows were intermediately ranked.

	Reproductive Trait	**RQ 1**	**RQ 2**	**RQ 3**	**RQ 4**	***P-value***
Farrowing	*Number born alive*	11.11 ± 1.03	10.96 ± 0.86	8.73 ± 0.98	9.76 ± 1.21	*0.22*
	Number dead at birth	0.72 ± 0.52	1.33 ± 0.46	1.3 ± 0.51	1.10 ± 0.64	*0.83*
	Number of mummies	0.01 ± 0.12	0.09 ± 0.11	0.05 ± 0.12	0.45 ± 0.15	*0.08*
	Total number farrowed	11.52 ± 1.06	12.30 ± 0.87	10.42 ± 1.00	11.72 ± 1.28	*0.53*
	Farrowing survival	88.0 ± 4.31	89.61 ± 3.58	85.18 ± 3.98	90.86 ± 5.19	*0.77*
	Number birth weight < 1 kg	1.45 ± 0.7	2.26 ± 0.59	2.09 ± 0.65	3.13 ± 0.84	*0.48*
	Total litter birth weight (kg)	18.86 ± 1.69	18.38 ± 1.51	16.01 ± 1.63	16.04 ± 2.22	*0.35*
	Number of piglets which failed to thrive	0.05 ± 0.20	0.12 ± 0.18	0.18 ± 0.23	0.27 ± 0.26	*0.93*
	Pre-weaning survival	86.89 ± 4.25	90.03 ± 3.60	85.65 ± 4.00	90.48 ± 5.22	*0.77*
Weaning	*Number of piglets with adjusted weaning weight < 4.5 kg*	0.78 ± .97	1.95 ± 0.66	1.69 ± 0.85	1.08 ± 0.93	*0.63*
	Litter weaning weight (kg)	58.06 ± 4.52	59.36 ± 3.87	50.73 ± 4.32	51.74 ± 5.44	*0.39*

2.4. Discussion

Precision livestock farming technology is capable of aiding livestock producers and researchers in detecting illness, injury, and poor welfare (Benjamin and Yik, 2019; Gómez et al., 2021). This study sought to investigate whether IRT, RFID, and HRV technologies could be used to identify group housed sow social hierarchies. The establishment of the social hierarchy is commonly observed in nature but could also be a welfare concern in group housing systems due to the occurrence of agonistic interactions and their negative impacts on sow welfare (Mcglone, 1986). The social hierarchy determines sows' abilities to access to limited resources and can leave sows at risk of poor welfare due to injury and stress (Salak-Johnson, 2017).

2.4.1. Infrared Thermal Imaging

In response to a stressor, the hypothalamic-pituitary axis is activated, and heat is generated due to increases in stress hormones (*i.e.*, cortisol) and blood flow. The increased blood circulation near the skin results in increased heat radiated from the body's surface (Stewart et al., 2005; Stewart et al., 2007). Infrared thermography offers a non-invasive method for capturing infrared radiation (heat) emitted by animals, which is then converted into a computer-generated image to evaluate the changes that occur. This technology has been used to detect changes in physiological processes related to changes in body surface temperature, including illness and thermal stress (Brown-Brandl et al., 2013; Cook et al., 2015; Salles et al., 2016). Additionally, IRT has been used to evaluate painful procedures and social stress in livestock species (Stewart, 2008; Boileau et al., 2019; Travain and Valsecchi, 2021).

Internal body temperature has been shown to increase under stress (Balcombe et al., 2004) and it could be assumed that animals lower in the social hierarchy would be under more stress (Marchant-Ford, 2010; Martínez-Miró et al., 2016). As a result, lowly-ranked animals would display elevated body surface temperatures. However, this has not been a consistent finding. For example, Boileau et al. (2019) captured thermal images of swine dyads during agonistic interactions and found there were no differences in body surface temperature between winners and losers of the encounters. Interestingly, the animals' temperatures dropped sharply after the encounter, which indicates that a thermal response does take place during aggressive interactions.

In the present study, no differences were found between RQ on any days of the experiment. This may be due to the timeline of IRT data collection, since images were not captured upon sow reintroduction to group gestation housing. There was, however, a day effect on IRT, where IRT mean temperatures decreased as the gestation period proceeded. This could be due to the decline in ambient temperature observed throughout the study and thermoregulatory processes which occur naturally. Additionally, this could also be attributed to animals becoming accustomed to one another over time and the decrease in stress which occurs after the social hierarchy is established. Future research should evaluate IRT immediately after reintroduction to group gestation housing. Moreover, different ROI should be investigated for use in PLF tool research related to sow welfare.

2.4.2. Feeding Behavior Traits

Electronic sow feeding systems were developed in the 1980s as an alternative feeding method to reduce aggression and competition over feed within groups of gestating sows (Lambert et al., 1983; Edwards et al., 1984). Although feeders within an ESF system can accommodate numerous sows based on the manufacturer recommendations, the fewer number of feeding spaces can result in competition and aggression between pen mates similar to competitive feeding methods (Spoolder and Vermeer, 2015; Norring et al., 2019).

Since social hierarchy is created in order to determine one’s access to limited resources (Meese and Ewbank, 1973; Stukenborg et al., 2011), competition to gain feeder space within an ESF system can be heightened and can increase aggression (Olsson et al., 2011; Jang et al., 2015). Sows of higher rank, or dominant sows, may have easier access to feed compared to lower ranking sows (Csermely and Wood-Gush, 1990), which can lead to body condition and weight variation within groups (Rasmussen et al., 1962).

Previous research has explored the social hierarchy and its relation to the feeding behavior using different feeding methods. In the current study, occupation time per ESF visit was greatest in RQ2, while RQ4 exhibited the least amount of time in the ESF. Rank quartile 1 and RQ3 sows were intermediate to RQ 2 and RQ 4 sows. This same pattern was also seen in occupation time per visit where sows received feed during the visit. These results indicate that higher ranking sows are occupying the feeder for longer periods of time, similar to previous research (Martin and Edwards, 1994; Salak-Johnson, 2017). It can also be inferred that these higher-ranking sows have priority access to feeding space compared to other sows due to their dominance and are able to enter the feeder before other sows, even when there are sows waiting to gain access who may not have consumed their entire daily allotment (Olsson et al., 2011; Brajon et al., 2021).

Rank quartile 1 and RQ2 sows made fewer ESF visits per day compared to RQ3 and RQ4 sows. Similarly, RQ1 and RQ2 sows made fewer ESF visits with feed per day compared to RQ 4 sows. This indicates that higher ranking sows are consuming a majority of their ration in a smaller number of visits but continuing to occupy feeding space for longer periods of time even when their ration is consumed. Lower-ranking sows may have adjusted their feeding habits to times when there is little pressure to access the feeder (*i.e.,* when higher-ranked pen mates are resting or sleeping throughout the day; Brajon et al., 2021). This has been reported in other studies utilizing both ESF and ad libitum feeding systems (Brouns and Edwards, 1994; Marchant Ford, 2010), which indicates that lower-ranking sows are capable of adapting to their environment and location within the hierarchy when feeding resources are limited. Further evidence of their ability to adapt has been reported in other previous studies where sow feeding behavior has changed throughout gestation when ESF settings have been altered (Vargovic et al., 2021)

Taken together, the feeding behavior results in the current study demonstrate that lower ranking sows may be consuming portions of the rations over numerous visits earlier in the day (*i.e.*, hours 4-8), which is in agreement with other studies (Anil et al., 2006; Chapinal et al., 2008). This could possibly be due to social pressure around the feeding spaces (Nielsen, 1999; Boumans et al., 2018). Although the feeders used within the current study were fully enclosed, sows within feeders were able to be seen by their conspecifics. As a result, the formation of a "feed queue" (Edwards et al., 1988; Hunter et al., 1988; Putten and Burgwal, 1990), or a line of sows surrounding the feeders, may create social pressure and stress for the sow inhabiting the ESF (Nielsen, 1999; Brajon et al., 2021). Research has found that pigs fed individually within an ESF system may be able to gain access to feeder space daily, however it is possible that some individuals may not consume their entire allotment due to intimidation from pigs waiting outside the feeder (Mendl et al., 1992).

2.4.3. HRV

Heart rate variability is a useful noninvasive measure for assessing livestock welfare (von Borell et al., 2007). Mean HR has been used in previous studies to determine the impacts of stressful stimuli on pigs and various livestock (De Jong et al., 2000; Mott et al., 2021). However, HRV offers more insight into the effect of various stressors on the autonomic nervous system. An animal's attempts to cope with a stressor leads to functional, structural, and behavioral adjustments in order to survive (Moberg, 2000). Heart rate variability is one advantageous measure for evaluating these adjustments since several HRV measures are capable of characterizing parasympathetic (and to a degree, sympathetic) activity in response to a stressor.

Average RR interval and SDNN differed between RQ during the baseline period (while sows were still housed in their farrowing stalls). A higher RR value is representative of lower mean heart rate and reduced stress. Compared to RQ3 and RQ4, RQ1 and RQ2 had greater RR intervals, with RQ 2 sows exhibiting the greatest RR. The SDNN in this study represents short-term parasympathetic activity, where greater SDNN values indicate greater parasympathetic activity and lower stress (Kovács et al., 2014). In the current study, RQ4 sows exhibited lower SDNN values compared to RQ2 and RQ3 sows. Interestingly, RQ1 sows exhibited similar SDNN compared to RQ4 sows. Accordingly, RQ2 sows exhibited the greatest SDNN and, therefore, greater levels of parasympathetic activity compared to all other RQ. These results could possibly be due to the impact of previous stressors on autonomic regulation (von Borell et al., 2007). The establishment of the social hierarchy can result in heightened stress for some individuals and social rank can impact physiological measures (*i.e.,* plasma cortisol, white blood cell count, etc.; Otten et al., 2001; Pacheco and Salak-Johnson, 2016). Therefore, previous social experience and rank could impact resting HRV measures, with future high-ranking and low-ranking sows exhibiting lower variation due to decreased parasympathetic activity.

Although no differences were found between RQ for any HRV measures during the post-mixing period, differences found in HRV measures prior to reintroduction to group gestation housing may indicate that certain HRV measures could be useful as predictors of future hierarchy placement. Future studies on this topic should also incorporate nonlinear measures of heart rate variability to investigate their effectiveness for characterizing the social hierarchy of group housed sows.

2.4.4. Liveweight Measurements

Sow body weight and condition transitions between the lactation and gestation period. During the gestation phase, sows on a nutrient dense, restricted diet (Mallmann et al., 2019) and are fed to maintain body weight. When transitioning from late gestation to lactation, sow rations are increased in order to meet the new energy requirement of milk production (Einarsson and Rojkittikhun, 1993). Interestingly, BCS decreased from baseline to all other days of the study while backfat depth increased as the gestation period progressed. A pattern of changing body condition can be found in other studies. Chapinal et al. (2010) and Pacheco and Salak-Johnson (2016) found that sow body weight (BW) did not differ between d1 and d15 of the experiment. While we did not collect BW throughout the study, sow BCS remained unaltered during the same period. However, sow BCS then decreased, which is contradictory to previously published results (Chapinal et al., 2010). This could be due to technical difficulties which occurred during the experiment. During the 3rd, 4th, and 5th repetition of the study, there were periods of time when the ESF did not dispense feed. Sows were then floor fed at approximately 2.2 kg of feed per day per sow. Therefore, due to aggression and competition over feed, some sows may not have received their full ration, leading to a decrease in BCS. The BF reported in the current study did align with previous research on the topic, where sow BF begins to increase from lactation to approximately d 60-65 of gestation (Chapinal et al., 2010). Other studies have also reported that BF can continue to increase until late gestation (Pacheco, 2016; Lavery et al., 2019).

2.4.5. Reproductive Performance

Social behaviors within group gestation housing systems, like aggressive interactions, can have negative effects on reproductive performance (Lagoda et al., 2021). Pacheco and Salak-Johnson (2016) found that dominant sows had a greater number of piglets born alive than subdominant sows. This is similar to other research, which found a greater total number of piglets born to high-ranking individuals (Hoy et al., 2009). Previous research has also reported that high ranking sows had greater or equal total number of piglets born compared to other social ranks but wean fewer piglets due to the greater number of stillborn piglets (Nicholson et al., 1993; Zhao et al., 2013). The current study found no differences between RQ for the total number of piglets farrowed or number of mummies per litter. Gestation length and parity were found to influence various reproductive performance measures in the current study. However, parity and gestation length were only included as a covariate in the reproductive statistical models and was not investigated at length.

Research findings investigating litter birthweight differences between social ranks is inconsistent. Dominant sows may farrow heavier or lighter piglets than subdominant sows (Mendl et al., 1992; Zhao et al., 2013). Additional studies have reported that higher-ranking sows produce lighter litter weaning weights (Zhao et al., 2013), while others suggest low-ranking sows have the lightest litter weaning weights (Kranendonk et al., 2007). However, the results in the current study suggest no differences in farrowing and weaning performance between sows of differing social rank which aligns with other previously published research (Nowachowicz et al., 1999; Brajon et al., 2021). Future research should investigate the impact of social rank on the reproductive performance of sows housed with an ESF to better clarify what, if any, influence social status has on reproduction.

2.5. Conclusions

Precision livestock farming technology has shown great promise aiding animal caretakers in the monitoring of animal health and welfare. Due to the welfare concerns which arise in group housed sows from the establishment of the social hierarchy, the objective of this study was to investigate the use of IRT characteristics, feeding activity obtained from an automated RFID feeding system, and HRV for detecting the social hierarchy within group housed sows. The study also aimed to determine the relationship between observed social hierarchy, feeding behavior traits, BCS, BF, and reproductive performance. Sows of higher rank occupied the ESF for longer periods of time while the lowest ranked sows (RQ4) occupied the ESF for the least amount of time but had a greater number of visits overall. These lowest ranking sows also consumed their ration in a greater number of visits per day early in the feeding period. Rank quartile was associated with baseline RR and SDNN HRV measures and indicate that low ranking sows exhibit greater stress than their high-ranking counterparts. Therefore, ESF feeding data and HRV technologies should be explored further as potential PLF technologies for determining group housed sow social hierarchies. Additionally, more research should also investigate how these technologies could aid animal caretakers in mitigating negative welfare outcomes due to sow social rank.

2.6. References

Anil, L., S. S. Anil, J. Deen, S. K. Baidoo, and R. D. Walker. 2006. Effect of group size and structure on the welfare and performance of pregnant sows in pens with electronic sow feeders. Can. J. Vet. Res. 70:128–136.

Arey, D. S., and S. A. Edwards. 1998. Factors influencing aggression between sows after mixing and the consequences for welfare and production. Livest. Prod. Sci. 56:61–70. doi:10.1016/S0301-6226(98)00144-4.

Balcombe, J. P., N. D. Barnard, and C. Sandusky. 2004. Laboratory routines cause animal stress. Contemp. Top. Lab. Anim. Sci. 43:42–51.

Barnett, J. L., P. H. Hemsworth, G. M. Cronin, E. C. Jongman, and G. D. Hutson. 2001. A review of the welfare issues for sows and piglets in relation to housing. Aust. J. Agric. Res. 4:269–281.

Bench, C. J., F. C. Rioja-Lang, S. M. Hayne, and H. W. Gonyou. 2013. Group gestation sow housing with individual feeding-II: How space allowance, group size and composition, and flooring affect sow welfare. Livest. Sci. 152:218–227. doi:10.1016/j.livsci.2012.12.020.

Benjamin, M., and S. Yik. 2019. Precision livestock farming in swine welfare: A review for swine practitioners. Animals. 9:1–21. doi:10.3390/ani9040133.

Boileau, A., M. Farish, S. P. Turner, and I. Camerlink. 2019. Infrared thermography of agonistic behaviour in pigs. Physiol. Behav. 210:112637. doi:10.1016/j.physbeh.2019.112637.

von Borell, E., J. Langbein, G. Després, S. Hansen, C. Leterrier, J. Marchant-Forde, R. Marchant-Forde, M. Minero, E. Mohr, A. Prunier, D. Valance, and I. Veissier. 2007. Heart rate variability as a measure of autonomic regulation of cardiac activity for assessing stress and welfare in farm animals - A review. Physiol. Behav. 92:293–316. doi:10.1016/j.physbeh.2007.01.007.

Boumans, I. J. M. M., I. J. M. de Boer, G. J. Hofstede, and E. A. M. Bokkers. 2018. How social factors and behavioural strategies affect feeding and social interaction patterns in pigs. Physiol. Behav. 194:23–40. doi:10.1016/j.physbeh.2018.04.032.

Brajon, S., J. Ahloy-Dallaire, N. Devillers, and F. Guay. 2021. Social status and previous experience in the group as predictors of welfare of sows housed in large semi-static groups. PLoS One. 16:1–26. doi:10.1371/journal.pone.0244704.

Brouns, F., and S. A. Edwards. 1994. Social rank and feeding behaviour of group-housed sows fed competitively or ad libitum. Appl. Anim. Behav. Sci. 39:225–235. doi:10.1016/0168-1591(94)90158-9.

Brown-Brandl, T. M., R. A. Eigenberg, and J. L. Purswell. 2013. Using thermal imaging as a method of investigating thermal thresholds in finishing pigs. Biosyst. Eng. 114:327–333. doi:10.1016/j.biosystemseng.2012.11.015.

Chapinal, N., J. L. Ruiz-de-la-Torre, A. Cerisuelo, M. D. Baucells, J. Gasa, and X. Manteca. 2008. Feeder use patterns in group-housed pregnant sows fed with an unprotected electronic sow feeder (Fitmix). J. Appl. Anim. Welf. Sci. 11:319–336. doi:10.1080/10888700802329939.

Chapinal, N., J. L. Ruiz de la Torre, A. Cerisuelo, J. Gasa, M. D. Baucells, J. Coma, A. Vidal, and X. Manteca. 2010. Evaluation of welfare and productivity in pregnant sows kept in stalls or in 2 different group housing systems. J. Vet. Behav. Clin. Appl. Res. 5:82–93. doi:10.1016/j.jveb.2009.09.046.

Cook, N. J., B. Chabot, T. Lui, C. J. Bench, and A. L. Schaefer. 2015. Infrared thermography detects febrile and behavioural responses to vaccination of weaned piglets. Animal. 9:339–348. doi:10.1017/S1751731114002481.

Csermely, D., and D. G. M. Wood-Gush. 1990. Agonistic behaviour in grouped sows. II. how social rank affects feeding and drinking behaviour. Bolletino di Zool. 57:55–58. doi:10.1080/11250009009355674.

Edwards, S. A., A. W. Armsby, and J. W. Large. 1984. An electronic individual feeding system for group-housed dry sows. Farms Build. Eng. 1:25.

Edwards, S. A., A. W. Armsby, and J. W. Large. 1988. Effects of Feed Station Design on the Behavour of Group-Housed Sows Using an Electronic Individual Feeding System. Livest. Prod. Sci. 19:511–522.

Einarsson, S., and T. Rojkittikhun. 1993. Effects of nutrition on pregnant and lactating sows. J. Reprod. Fertil. Suppl. 48:229–239. doi:10.1530/biosciprocs.14.0016.

Elmore, M. R. P., J. P. Garner, A. K. Johnson, R. D. Kirkden, B. T. Richert, and E. A. Pajor. 2011. Getting around social status: Motivation and enrichment use of dominant and subordinate sows in a group setting. Appl. Anim. Behav. Sci. 133:154–163. doi:10.1016/j.applanim.2011.05.017.

Farrar, K. L., A. E. Field, S. L. Norris, and K. O. Jacobsen1. 2020. Comparison of rectal and infrared thermometry temperatures in anesthetized swine (sus scrofa). J. Am. Assoc. Lab. Anim. Sci. 59:221–225. doi:10.30802/AALAS-JAALAS-19-000119.

Gómez, Y., A. H. Stygar, I. J. M. M. Boumans, E. A. M. Bokkers, L. J. Pedersen, J. K. Niemi, M. Pastell, X. Manteca, and P. Llonch. 2021. A Systematic Review on Validated Precision Livestock Farming Technologies for Pig Production and Its Potential to Assess Animal Welfare. Front. Vet. Sci. 8:1–20. doi:10.3389/fvets.2021.660565.

Greenwood, E. C., K. J. Plush, W. H. E. J. van Wettere, and P. E. Hughes. 2014. Hierarchy formation in newly mixed, group housed sows and management strategies aimed at reducing its impact. Appl. Anim. Behav. Sci. 160:1–11. doi:10.1016/j.applanim.2014.09.011.

Halachmi, I., and M. Guarino. 2016. Editorial: Precision livestock farming: A “per animal” approach using advanced monitoring technologies. Animal. 10:1482–1483. doi:10.1017/S1751731116001142.

Hoy, S., J. Bauer, C. Borberg, L. Chonsch, and C. Weirich. 2009. Impact of rank position on fertility of sows. Livest. Sci. 126:69–72. doi:10.1016/j.livsci.2009.05.018.

Hunter, E. J., D. M. Broom, S. A. Edwards, and R. M. Sibly. 1988. Social hierarchy and feeder access in a group of 20 sows using a computer-controlled feeder. Anim. Prod. 47:139–148. doi:10.1017/S0003356100037144.

Jang, J. C., S. W. Jung, S. S. Jin, S. J. Ohh, J. E. Kim, and Y. Y. Kim. 2015. The effects of gilts housed either in group with the electronic sow feeding system or conventional stall. Asian-Australasian J. Anim. Sci. 28:1512–1518. doi:10.5713/ajas.14.0819.

Jensen, P. 1980. An ethogram of social interaction patterns in group-housed dry sows. Appl. Anim. Ethol. 6:341–350. doi:10.1016/0304-3762(80)90134-0.

De Jong, I. C., A. Sgoifo, E. Lambooij, S. M. Korte, H. J. Blokhuis, and J. M. Koolhaas. 2000. Effects of social stress on heart rate and heart rate variability in growing pigs. Can. J. Anim. Sci. 80:273–280. doi:10.4141/a99-085.

Kirkwood, R., and A. J. Zanella. 2005. Influence of Gestation Housing on Sow Welfare and Productivity. East Lansing.

Knauer, M. T., and D. J. Baitinger. 2015. The sow body condition caliper. Appl. Eng. Agric. 31:175–178. doi:10.13031/aea.31.10632.

Kovács, L., V. Jurkovich, M. Bakony, O. Szenci, P. Póti, and J. Tå'Zsér. 2014. Welfare implication of measuring heart rate and heart rate variability in dairy cattle: Literature review and conclusions for future research. Animal. 8:316–330. doi:10.1017/S1751731113002140.

Kranendonk, G., H. Van Der Mheen, M. Fillerup, and H. Hopster. 2007. Social rank of pregnant sows affects their body weight gain and behavior and performance of the offspring. J. Anim. Sci. 85:420–429. doi:10.2527/jas.2006-074.

Lagoda, M. E., L. A. Boyle, J. Marchewka, and J. A. Calderón Díaz. 2021. Mixing aggression intensity is associated with age at first service and floor type during gestation, with implications for sow reproductive performance. Animal. 15. doi:10.1016/j.animal.2020.100158.

Lambert, R., M. Ellis, P. Rowlinson, and C. Saville. 1983. Influence of housing/feeding system on sow behaviour. Anim. Prod. 36:1983.

Langbein, J., and B. Puppe. 2004. Analysing dominance relationships by sociometric methods - A plea for a more standardised and precise approach in farm animals. Appl. Anim. Behav. Sci. 87:293–315. doi:10.1016/j.applanim.2004.01.007.

Lavery, A., P. G. Lawlor, E. Magowan, H. M. Miller, K. O'driscoll, and D. P. Berry. 2019. An association analysis of sow parity, live-weight and back-fat depth as indicators of sow productivity. Animal. 13:622–630. doi:10.1017/S1751731118001799.

Liu, X., P. Song, H. Yan, L. Zhang, L. Wang, L. S. Fuping Zhao Xinhua Hou, B. Li, and and L. Wang. 2021. A Comparison of the Behavior, Physiology, and Offspring Resilience of Gestating Sows When Raised in a Group Housing System and Individual Stalls. Animals. 11:2076. doi:10.3390/ani11072076.

Maes, D., L. Pluym, and O. Peltoniemi. 2016. Impact of group housing of pregnant sows on health. Porc. Heal. Manag. 2:1–7. doi:10.1186/s40813-016-0032-3.

Mallmann, A. L., D. P. Fagundes, C. E. Vier, G. S. Oliveira, A. P. G. Mellagi, R. R. Ulguim, M. L. Bernardi, U. A. D. Orlando, R. J. Cogo, and F. P. Bortolozzo. 2019. Maternal nutrition during early and late gestation in gilts and sows under commercial conditions: Impacts on maternal growth and litter traits1. J. Anim. Sci. 97:4957–4964. doi:10.1093/jas/skz349.

Marchant-Ford, N. J. 2010. Social behvaior in swine and its impact on welfare. In: 21st IPVS Congress. p. 36–39.

Marchant-Forde, R. M., D. J. Marlin, and J. N. Marchant-Forde. 2004. Validation of a cardiac monitor for measuring heart rate variability in adult female pigs: Accuracy, artefacts and editing. Physiol. Behav. 80:449–458. doi:10.1016/j.physbeh.2003.09.007.

Martin, J. E., and S. A. Edwards. 1994. Feeding behaviour of outdoor sows: the effects of diet quantity and type. Appl. Anim. Behav. Sci. 41:63–74. doi:10.1016/0168-1591(94)90052-3.

Martínez-Miró, S., F. Tecles, M. Ramón, D. Escribano, F. Hernández, J. Madrid, J. Orengo, S. Martínez-Subiela, X. Manteca, and J. J. Cerón. 2016. Causes, consequences and biomarkers of stress in swine: An update. BMC Vet. Res. 12:1–9. doi:10.1186/s12917-016-0791-8.

Mcglone, J. J. 1986. Influence of resources on pig aggression and dominance. Behav. Processes. 12:135–144.

Meese, G. B., and R. Ewbank. 1973. The establishment and nature of the dominance hierarchy in the domesticated pig. Anim. Behav. 21:326–334. doi:10.1016/S0003-3472(73)80074-0.

Mendl, M., A. J. Zanella, and D. M. Broom. 1992. Physiological and reproductive correlates of behavioural strategies in female domestic pigs. Anim. Behav. 44:1107–1121. doi:10.1016/S0003-3472(05)80323-9.

Moberg, G. P. 2000. Biological response to stress: implications for animal welfare. Biol. Anim. Stress. 1–21.

Mott, R., F. Dowell, and N. Evans. 2021. Use of the Polar V800 and Actiheart 5 heart rate monitors for the assessment of heart rate variability (HRV) in horses. Appl. Anim. Behav. Sci. 241:5–10. doi:10.1016/j.applanim.2021.105401.

Munsterhjelm, C., A. Valros, M. Heinonen, O. Hälli, and O. A. T. Peltoniemi. 2008. Housing during early pregnancy affects fertility and behaviour of sows. Reprod. Domest. Anim. 43:584–591. doi:10.1111/j.1439-0531.2007.00956.x.

Nicholson, R. I., J. J. McGlone, and R. L. Norman. 1993. Quantification of stress in sows: comparison of individual housing versus social penning. J. Anim. Sci. 71:112.

Nielsen, B. L. 1999. On the interpretation of feeding behaviour measures and the use of feeding rate as an indicator of social constraint. Appl. Anim. Behav. Sci. 63:79–91. doi:10.1016/S0168-1591(99)00003-9.

Norring, M., A. Valros, P. Bergman, J. N. Marchant-Forde, and M. Heinonen. 2019. Body condition, live weight and success in agonistic encounters in mixed parity groups of sows during gestation. Animal. 13:392–398. doi:10.1017/S1751731118001453.

Nowachowicz, J., G. Michalska, W. Kapelański, and J. Kapelańska. 1999. Influence of electronically controlled individual feeding on behaviour and reproductive performance of pregnant sows. J. Anim. Feed Sci. 8:45–49. doi:10.22358/jafs/68806/1999.

Olsson, A. C., M. Andersson, J. Botermans, D. Rantzer, and J. Svendsen. 2011. Animal interaction and response to electronic sow feeding (ESF) in 3 different herds and effects of function settings to increase capacity. Livest. Sci. 137:268–272. doi:10.1016/j.livsci.2010.10.014.

Otten, W., B. Puppe, E. Kanitz, P. C. Schön, and B. Stabenow. 2002. Physiological and behavioral effects of different success during social confrontation in pigs with prior dominance experience. Physiol. Behav. 75:127–133. doi:10.1016/S0031-9384(01)00630-8.

Pacheco, E. 2016. Assessing the well-being of gestating submissive sows in group pens using multiple welfare metrics. doi:10.1016/j.jplph.2009.07.006%0A

Pacheco, E., and J. L. Salak-Johnson. 2016. Social Status Affects Welfare Metrics of Group-Housed Gestating Sows. J. Vet. Res. Anim. Husb. 1:103.

Pai, A., A. Veeraraghavan, and A. Sabharwal. 2021. HRVCam: robust camera-based measurement of heart rate variability. J. Biomed. Opt. 26:1–23. doi:10.1117/1.jbo.26.2.022707.

Putten, G. Van, and J. Van de Burgwal. 1990. Vulva biting in group-housed sows: preliminary report. Appl. Anim. Behav. Sci. 26:181–186.

Rasmussen, O. G., E. M. Banks, T. H. Berry, and D. E. Becker. 1962. Social dominance in gilts. J. Anim. Sci. 21:50–522.

Rocha, L. M., N. Devillers, X. Maldague, F. Z. Kabemba, J. Fleuret, F. Guay, and L. Faucitano. 2019. Validation of anatomical sites for the measurement of infrared body surface temperature variation in response to handling and transport. Animals. 9:1–18. doi:10.3390/ani9070425.

Salak-Johnson, J. L. 2017. Social status and housing factors affect reproductive performance of pregnant sows in groups. Mol. Reprod. Dev. 84:905–913. doi:10.1002/mrd.22846.

Salles, M. S. V., S. C. da Silva, F. A. Salles, L. C. Roma, L. El Faro, P. A. Bustos Mac Lean, C. E. Lins de Oliveira, and L. S. Martello. 2016. Mapping the body surface temperature of cattle by infrared thermography. J. Therm. Biol. 62:63–69. doi:10.1016/j.jtherbio.2016.10.003.

Sapolsky, R. M. 2004. Social status and health in humans and other animals. Annu. Rev. Anthropol. 33:393–418. doi:10.1146/annurev.anthro.33.070203.144000.

Soerensen, D. D., S. Clausen, J. B. Mercer, and L. J. Pedersen. 2014. Determining the emissivity of pig skin for accurate infrared thermography. Comput. Electron. Agric. 109:52–58. doi:10.1016/j.compag.2014.09.003.

Spoolder, H. A. M., M. J. Geudeke, C. M. C. Van der Peet-Schwering, and N. M. Soede. 2009. Group housing of sows in early pregnancy: A review of success and risk factors. Livest. Sci. 125:1–14. doi:10.1016/j.livsci.2009.03.009.

Spoolder, H. A. M., and H. M. Vermeer. 2015. Gestation group housing of sows. In: The gestating and lactating sow. p. 47–72.

Stewart, M. 2008. Non-invasive measurment of stress and pain in cattle using infrared thermography: a thesis submitted in partial fulfillment of the requirements for the degreee of Doctor of Philosophy in Animal Science. Massey University, Palmerston North, New Zealand. p. 49-60, 65-85, 109-128.

Stewart, M., J. R. Webster, A. L. Schaefer, N. J. Cook, and S. L. Scott. 2005. Infrared thermography as a non-invasive tool to study animal welfare. Anim. Welf. 14:319–325.

Stewart, M., J. R. Webster, G. A. Verkerk, A. L. Schaefer, J. J. Colyn, and K. J. Stafford. 2007. Non-invasive measurement of stress in dairy cows using infrared thermography. Physiol. Behav. 92:520–525. doi:10.1016/j.physbeh.2007.04.034.

Stukenborg, A., I. Traulsen, B. Puppe, U. Presuhn, and J. Krieter. 2011. Agonistic behaviour after mixing in pigs under commercial farm conditions. Appl. Anim. Behav. Sci. 129:28–35. doi:10.1016/j.applanim.2010.10.004. Available from: http://dx.doi.org/10.1016/j.applanim.2010.10.004

Tolkamp, B. J., D. J. Allcroft, J. P. Barrio, T. A. G. Bley, J. A. Howie, T. B. Jacobsen, C. A. Morgan, D. P. N. Schweitzer, S. Wilkinson, M. P. Yeates, and I. Kyriazakis. 2011. The temporal structure of feeding behavior. Am. J. Physiol. - Regul. Integr. Comp. Physiol. 301:378–393. doi:10.1152/ajpregu.00661.2010.

Travain, T., and P. Valsecchi. 2021. Infrared thermography in the study of animals' emotional responses: A critical review. Animals. 11. doi:10.3390/ani11092510.

Val-Laillet, D., A. M. de Passillé, J. Rushen, and M. A. G. von Keyserlingk. 2008. The concept of social dominance and the social distribution of feeding-related displacements between cows. Appl. Anim. Behav. Sci. 111:158–172. doi:10.1016/j.applanim.2007.06.001.

Vargovic, L., S. Hermesch, R. Z. Athorn, and K. L. Bunter. 2021. Feed intake and feeding behaviour traits of gestating sows are associated with undesirable outcomes. Livest. Sci. 249:104526. doi:10.1016/j.livsci.2021.104526.

Verdon, M., C. F. Hansen, J. L. Rault, E. Jongman, L. U. Hansen, K. Plush, and P. H. Hemsworth. 2015. Effects of group housing on sow welfare: A review. J. Anim. Sci. 93:1999–2017. doi:10.2527/jas.2014-8742.

Wang, M., A. Youssef, M. Larsen, J. L. Rault, D. Berckmans, J. N. Marchant-Forde, J. Hartung, A. Bleich, M. Lu, and T. Norton. 2021. Contactless video-based heart rate monitoring of a resting and an anesthetized pig. Animals. 11:1–14. doi:10.3390/ani11020442.

Zhao, Y., W. L. Flowers, A. Saraiva, K. J. Yeum, and S. W. Kim. 2013. Effect of social ranks and gestation housing systems on oxidative stress status, reproductive performance, and immune status of sows1. J. Anim. Sci. 91:5848–5858. doi:10.2527/jas.2013-6388.