Production and welfare of sows and pigs in lactation

by

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B.S., Kansas State University, 2014
M.S., Iowa State University, 2017

AN ABSTRACT OF A DISSERTATION

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Abstract

Welfare of pigs has become a larger issue in the United States in recent years. The evolution of production facilities and production schemes require investigation into the performance of sows and piglets. Especially given public perception and changing regulations regarding food production. The use of technology as a strategy to decrease preweaning mortality may have detrimental effects on the sows and should be explored. Fifty-six sows treated with wearable novel technology to reduce preweaning mortality showed more exaggerated behavioral response to a simulated piglet crushing event by jumping or rising to a standing position more than control sows ($P < 0.01$). Sows treated with novel technology did not, however, show any greater physiological response to treatment than control sows ($P > 0.10$). Piglet birth order and management status (transferred or not) as well as sow treatment in lactation impact future piglet performance and welfare. The application of aversive stimuli to sows disrupted nursing stability. More piglets in VIB+EI treatment missed nursing bouts over the course of treatment (P=0.001). Birth order was grouped into categories (piglets born 1-5, 6-11, 12-18, 19-21) and transferred piglets. Earlier born piglets had a shorter latency to suckle ($P = 0.05$). Piglets that were transferred were more likely to move toward the sows head to suckle ($P = 0.09$). Transfer piglets and piglets in birth category three were less consistently in the same teat quadrant ($P = 0.05$) compared to earlier or late born piglets. Piglet weight was taken at birth, day seven and weaning. Transfer piglets were largest throughout, and latest born piglets gained a higher percentage of body weight over the course of lactation ($P < 0.05$). Multiple technological advances have been developed to both mitigate the loss of piglets around parturition, as well as increase their, and the sows welfare. The varying designs and results of which consistently indicate mortality risk is greater within early life and restricting sow movement is a common theme to prevent

loss.Technology, and its impact on pork production is an evolving relationship. The use of novel technology can positively impact production numbers without impacting the overall welfare of the sows or piglets.

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Dedication

For my family; throughout this journey that has been my education, the only constant has been your support. Mom and Dad, you have sacrificed and gone out of your way to afford me every opportunity in life, and fostered my passion from day one, regardless of its direction. I've learned a lot from books, but most importantly you taught me how to work hard and continue to pursue my passions. One of my regrets is that I learned too late that I was on the same path of my grandparents. After that knowledge, it became one of my proudest accomplishments to know that I can somehow be like them. Grandpa Mumm, I wish I knew that the years we spent in a pig barn would be the beginning and the foundation of what I do know, I would have tried to learn more. It gives me more pride than I can define to know that I may be somehow following in your footsteps. Grandpa Harlan, it's easy to go about life knowing that I have the best role model that a young man can look up to. Hard work, perseverance and dedication to the highest level of quality in all aspects of life are things that you gave me worth more than any knowledge books ever could. My accomplishments pale in comparison to the lives that my family has built before me. To you all, I hope that I make you proud, and understand that I am already proud to point towards my family as a large part of any personal accomplishment. Regardless of where I end up, I am confident in the example that has been set for me by you all, and in knowing that everything else will fall into place. These words don't do any justice for all that you've done for me; I hope that by me pursuing my passion with all the dedication and hard work that I learned through you, can in some way represent how much you have all meant to me in my life.

Preface

The climate of the commercial hog industry has been in a state of progress and change in the last three decades. By moving from production practices such as loose farrowing and group housing in the 1950's and 1960's, to the current confined operations that value more throughput and product with economies of scale. Now, research advances in animal psychology and wellbeing have driven work towards technological advances that meet both production and welfare needs. In combination with physiological and objective measurements that have been a cornerstone of production and animal science for generations, the holistic approach to swine production that is currently sought combines the highest level of animal well-being with the highest level of production possible. The focus herein will be on the lactation phase of production, from the perspective of both sow and piglets. This initial phase of pork production is paramount for maintaining production in later phases, as well as providing a safe affordable protein worldwide.

Chapter 1 - Swine in Lactation: what we know, Shortfalls and Potential

In the United States (US), large systems dominate the landscape of swine production. Thus, the time in the lactation phase is driven down from the natural 20-137 days (Newberry and Woodgush, 1985; Horback, 2014), to 20.8 days (Stalder, 2017) in controlled commercial environments. Despite the extremely short window in the production scheme, the lactation period is the main economic driver in swine production. Both the sows and the piglets' maintenance, growth, health and welfare have direct impact on the future success of the production system. Currently, for the top 25 % of US farms, the number of pigs/mated sow/year, which directly impacts downstream production numbers of any swine farm, is 29.1 pigs from 2.58 litters/year (Stalder, 2017). Weaning 11.3 pigs per litter out of 13.1 pigs born equates to a 13.6 % preweaning mortality (Stalder, 2017) for the top 25 % of farms in the US. All US farms on average report numbers of 12.6 pigs born alive, 10.3 pigs weaned and 17.5 % preweaning mortality (Stalder, 2017). These benchmark data establish the critical point of swine production as it moves on to later stages and marks areas of interest for improvement during the lactation phase. This review will identify practices in lactation as they relate to maintaining or increasing production, as well as the shortfalls in those practices and ways to minimize or eliminate them. The following will visit the past, current, and potential future industry approaches from the perspective of both the sow and the piglets in the lactation phase, to maximize their production and welfare.

Sows

Much effort, in both a production setting and research, has been put into maintaining the nutrition of the sow during lactation. Recent efforts, driven by a societal movement toward more positive animal welfare, have brought renewed interest in sow housing. The sow has the unique task of transitioning from a limit fed diet during gestation, to tremendous energy expenditure while attempting to maintain body reserves during lactation (Prunier et al., 2010). Both the aspects of nutrition management and the environment contribute as points of concern for the welfare of modern sows.

There exists a delicate balance between a sow building enough body reserves for lactation and over conditioning herself to cause problems during the farrowing process or lactation feed intake (Dourmad et al., 2008). Thus, modern sows are fed restricted diets during gestation. Feyera and Theil (2017) performed a comprehensive study on the energy requirements of sows in late gestation throughout lactation. The energy requirements of sows in late gestation, accounting for sow maintenance as well as the fetal growth, were estimated at 440 kJ per day per kg of body weight (Feyera and Theil, 2017). This estimation included energy requirements for sows that were assumed to be in optimal body condition, and were housed such that nestbuilding prior to parturition was available. Physical activity of sows increases their energy requirements (Dourmad et al., 2008). Though most sows in the US are not offered substrate to nest build. Similarly sows that are over or underconditioned require adjustments to feed energy (NRC, 2012). As the sows transition to lactation, the requirements for energy increase to 460 kJ per day per kg (Feyera and Theil, 2017; Dourmad et al., 2008). The additional inputs to milk production contribute to this increase. Dourmad et al. (2008) makes note that energy requirements for lactating sows are less variable as they are less active and maintained at a temperature above the lower critical temperature (LCT), meaning no energy is needed for heat production. Similarly, the National Research Council in the United States utilizes the following model to calculate maintenance energy for sows: Standard maintenance (ME) requirements (kcal/day) = 100 x (total

$BW)^{0.75}$ (NRC, 2012). Allowances for critical temperature zones and activity level are accounted for by increasing kcal/day by 4.30 and 2.39 for each degree C below the LCT and group housing respectively (NRC, 2012). Other additions to the energy levels of sows that allow for variables such as the uterine body and uterine fluid increase, number of piglets, age of sow, and body condition of sow are specifically reviewed by the National Research Council (NRC, 2012). The importance of managing the nutrition and energy of sows is paramount for positive welfare status. Especially in the instance of meeting their freedom from hunger, freedom from fear and distress, and freedom from disease (Brambell, 1965). If utilizing the performance axiom developed by Curtis (2007), which relies heavily on production output, the sow's litter weight and piglet production may excel but her individual welfare state may suffer. When applying the more modern frameworks of Fraser (2008) or Mellor (2016), the satiety and health of the sow becomes more of an ethical dilemma, as hunger contributes to a negative welfare state and should be addressed.

The issues of hunger and physical welfare of the sow are much more prevalent in the gestation phase, and that carryover is directly related to lactation. The US production systems include operations that have no requirement for group housing. Thus, limiting the hunger of sows in stalled housing is important. The stalled sow allows for overt display of stereotypic behaviors (e.g. bar biting, sham chewing) (Broom et al., 1995). The ontogeny of these stereotypic behaviors can be traced to frustrations on the part of the animal driven by hunger or frustration (Koolhaas et al., 1999). To potentially limit these behaviors from a stalled sow perspective, Huang et al. (2020) showed that including 5% resistant starch in the diet increased gut swelling, decreased standing, and tended to decrease cortisol concentrations compared to control or a fermented soybean diet. Numerical differences were seen in the amount of sham chewing, but no statistical significance was found. Equally as important, there were no differences in sows and piglets in terms of numbers born and litter performance measures (Huang et al., 2020). The growing body of literature that is utilizing higher fiber diets to increase the satiety of sows in gestation is a positive movement toward increasing the welfare of commercial sows, regardless of housing, worldwide. Sow nutrition is merely one aspect of overall sow welfare. Another hotly debated aspect is sow housing.

Sow housing can be discussed in two phases; gestation, and lactation. Gestation housing is pushing towards group systems worldwide and in the US (Council Directive 2008/120/EC; ASPCA 2020). The literature discussing sow production and welfare is vast: outlining space requirements (Curtis et al., 1989; Anil et al., 2002; McGlone et al., 2004), sow behaviors including stereotypies (Marchant and Broom, 1996; Dailey and McGlone, 1997; Anil et al., 2002; Anil et al., 2006), and production measures such as number born, preweaning mortality, weaning performance, and reproductive performance (Bates et al., 2003; Lammers et al., 2007; Vande Pol et al., 2018). From a sow performance perspective, using gestation stalls or group housing systems is a relative stalemate (Marchant-Forde, 2010). However, the restrictive nature of the gestation stall confines animals such that their freedom to express natural behaviors is compromised (Brambell, 1965) or their ability to pursue natural living is limited (Fraser, 2008). The focus of this review is on the lactation phase of swine production, thus the welfare implications from remaining restricted to a stall for the course of gestation, then moving to a restrictive environment for farrowing and lactation will be discussed. Along with moving from an open group housed environment in gestation to the restrictive environment of farrowing and lactation, as this offers differing welfare tradeoffs.

The transition to a farrowing and lactation environment from any type of gestation housing is an environmental change for sows. Each animal copes with this change differently allowing potential for decreased welfare (Koolhaas et al., 1999; Yin et al., 2020). The instinctual drive for sows to nest build prior to parturition (Wischner et al., 2009) is largely removed in the US, especially due to lack of substrate in farrowing houses. This causes frustration and an increase in stress as measured physiologically (heart rate; Boyle et al., 2000) and behaviorally (Boyle et al., 2002; McGlone et al., 2004; Yin et al., 2020). This stressor directly impacts both the freedom to express natural behavior and the goal of meeting an animals' ability for natural living (Brambell, 1965; Fraser, 2008). The frustration and negative affective state of the sows is important in and of itself. However, any disturbance to the sow that detracts from her optimum well-being and output has the potential to detract from the production of the piglets.

Multiple studies have examined gestation housing in regards to the number of piglets born and number of piglets born alive, with varying results based on gestational housing strategies (Yin et al., 2020). The performance of the piglets in terms of growth, as well as the sows ensuing reproductive performance, has been markedly different (Kim et al., 2016). Similarly, King et al. (2018) noted that piglet survival rate increased when sows were allowed to farrow in similar conditions to their previous farrowing experience (crates or pens). Koolhaas et al. (1999), Jarvis et al. (2004), and Pedersen et al. (2020) all describe the capabilities of sows to feel and develop frustration or stress around the time of farrowing due to the change in environment and the physiological changes and pain for piglet expulsion as well. Jarvis et al. (2004) implicates sow aggression and the frustration of being confined in barren farrowing environments to piglet savaging in primiparous sows in pen farrowing, thus decreasing sow and piglet welfare. Equally as important to the psychological well-being of periparturient sows, Daigle (2018) describes postpartum depression and loss of appetite which can be a physical detriment to the animals. There exist multiple advances in farrowing technology to increase the welfare of sows in farrowing crates. Examples of which are modifying the crate to increase the size for larger sows, installing adjustable crates that can be opened to mimic a pen after the initial days of lactation, or using an open pen (Pedersen et al., 2020). The European Union is the leader in these advances along with legislation requiring the use of substrate for nest building (Council Directive, 2008). However, adjustments to increase the sows space allowance to include turning around, while resulting in more controlled lying down (Hobel et al., 2018), also increase piglet mortality due to crushing by the sow (Marchant et al., 2000; Weber et al., 2007). Thus, there exist trade-offs between the sow welfare and the welfare of the piglets to be discussed in later sections. Beyond the hormonal and psychological changes that sows are required to make around parturition there also exists distrubances to welfare from the standpoint of heat and cold stress.

Temperature stress in sows can be due to heat or cold, noted as the upper or lower critical temperatures (UCT or LCT) (Pedersen et al., 2020), with thermoneutral seen between 16 to 20° C (Williams et al., 2013; Pedersen et al., 2020). Most discrepancies to the thermoneutral zone of sows are seen in direction of heat stress as this is more difficult to combat. Heat stress in sows negatively impacts sow appetite backfat, and piglet weaning weight along with increasing the sows respiration rate (Muns et al., 2016a). Sows that farrow in pens are able to thermoregulate by seeking out cooler floor areas (Pedersen et al., 2020). Otherwise mechanical cooling must be used to allow animals to dissipate heat. The options for mechanical cooling are numerous. Most recently, cooling pads using flowing water underneath the sow to reduce heart rate and body position changes indicate greater sow comfort (Parois et al., 2018). The use of water via fogging machines to reduce sow respiration and rectal temperature is also available (Godyn et al., 2018);

however, this method does increase the humidity in the room which detracts from evaporative cooling. Other means of cooling sows, especially in lactation include pressurized air stream cooling, snout cooling, and drip cooling (Barbari and Conti, 2009), and also increasing air velocity, radiative cooling, and sprinklers (Bjerg et al., 2019). The efficacy of any cooling system to reduce the heat stress on sows can be measured by physiological and behavioral responses such as heart rate (Parois et al., 2018; Bjerg et al.,2019), respiration rate (Bjerg et al., 2019), rectal temperature (Dong et al., 2001, Bjerg et al., 2019), and sow location (Barbari and Conti, 2009). The goals of maintaining sows in the thermal neutral zone are synonymous with the goals for sows maintaining appetite and feed consumption during lactation and have been outlined previously. The use of any mechanical cooling in lactation to reduce the heat stress and improve the welfare of sows has potential for the exact opposite effect on the piglets, thus great care should be taken to establish and maintain micro-environments where piglets can optimize their welfare.

Piglets

Economics of swine production indicate that increasing piglet number and growth rate preferable (Stalder, 2017). To do this, mortality prior to weaning should be as low as possible (Muns et al., 2016b; Stalder, 2017). Preweaning mortality is a multifaceted problem in the swine industry (Muns et al., 2016b). Thermoregulation, and antibody transfer will be more thoroughly discussed in this section.From the colostrum intake perspective, Decaluwé et al. (2014) notes that shorter time to a piglets first suckling after birth equates to higher survival. The use of colostrum is two-fold, immunological and thermoregulatory. Quesnel et al. (2012) estimates that 200 g of colostrum are required per piglet within 24 h of birth to provide adequate immunity and reduce preweaning mortality. Piglets with IgG blood concentrations between (from sow colostrum at 24 h post birth) 2250 and 2500 mg/dl had a 91% survival rate at weaning (Cabrera et al., 2012). Newborn pigs rely on maternal antibodies in colostrum, milk, and mammary secretions until approximately 4 weeks of age (Le Dividich et al., 2005; Poonsuk and Zimmerman, 2018). In keeping with substantiated welfare rhetoric such as the freedom from disease or basic health and functioning (Brambell, 1965; Fraser, 2008), a properly working immune system is paramount for newborn piglets. To corroborate this Ogawa et al. (2016) deprived piglets of sow colostrum for the first 24 hours of life, after which they were reared with their birth sow and littermates. At 21 days of age fecal samples of immunoglobulin A and G were collected. Piglets deprived of maternal colostrum had significantly lower IgA and IgG levels (Ogawa et al., 2016) than those that remained on the sow. The lack of proper immunity throughout life is a long-term issue, whereas thermoregulatory benefits of colostrum consumption immediately post birth are more immediate.

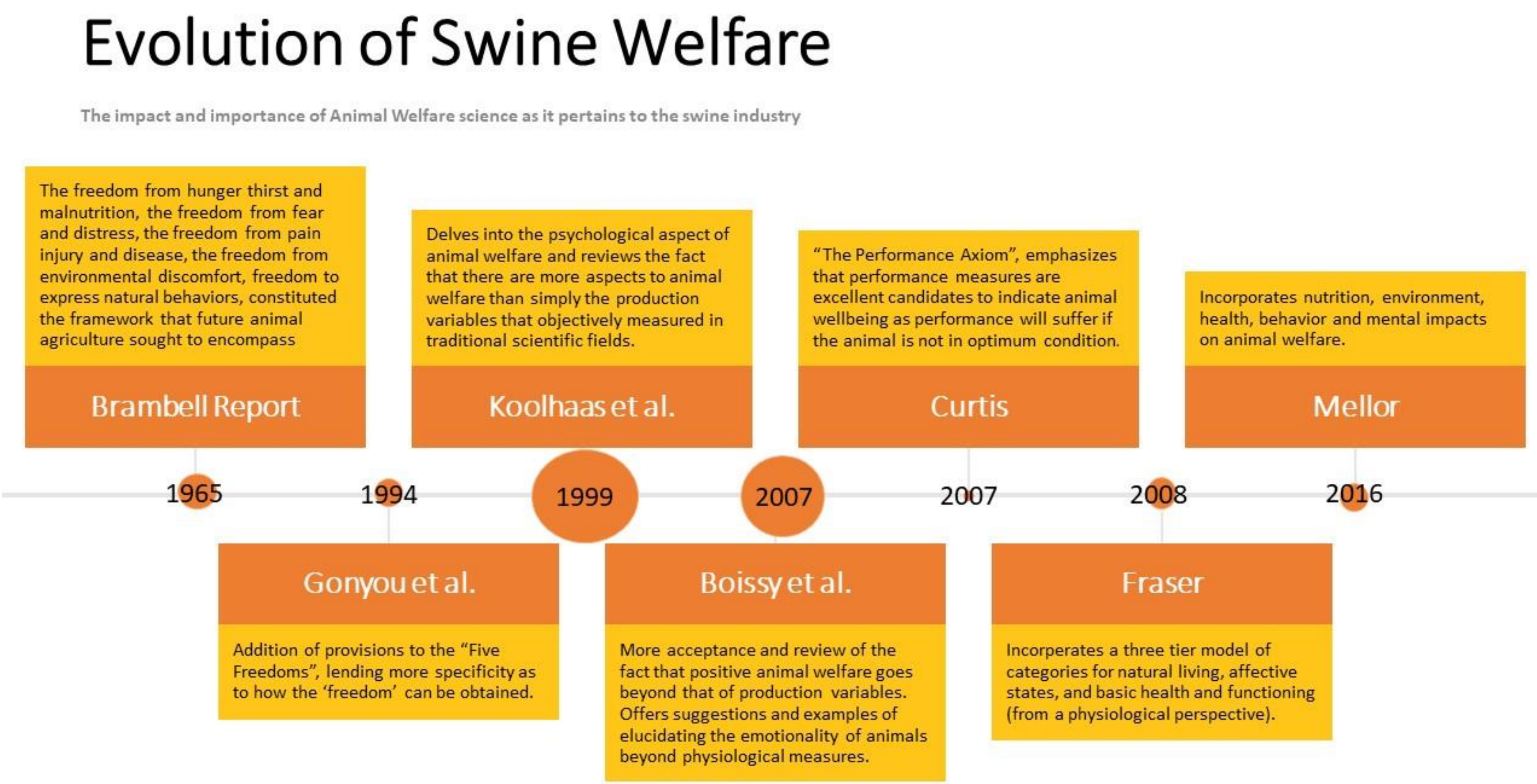
Piglet rectal temperature is a commonly gathered variable and gives insight to the body temperature of piglets in the hours after birth. Lower rectal temperatures coincide with greater mortality 24 hours after birth (Tuchscherer et al., 2000; Nuntapaitoon et al., 2018). Piglets have very little ability to generate endogenous heat, due to the lack of brown adipose tissue and limited body mass or energy reserves to initiate shivering (Andersen and Pedersen, 2016). Common production practice to mitigate body temperature loss is to develop a micro-environment within the crate where piglets are offered an alternative heat source (Larsen et al., 2017; Morello et al., 2017; Lane, 2019; Leonard et al., 2020). The goal is not only to increase the body temperature of piglets immediately after birth, but draw them away from the sow while resting to minimize the potential of piglet mortality by crushing.

Currently, a majority of preweaning mortality (barring disease outbreak in isolated situations) can be attributed to crushing (Weary et al., 1996; Knauer and Hostetler, 2013). Worldwide, the most simple mitigation to piglets being crushed by the sow is the farrowing crate. The decrease in piglet mortality in farrowing crates is dramatic with Marchant Forde (2000) reporting 8 % crushing in crates vs 14-17 % crushing in open housed systems. Jarvis et al. (2004) indicates that the crushing rate in traditional farrowing crates is roughly half that of crushing rate in pens with substrate, 5.6% and 12.1% respectively. The risk for crushing mortality is greatest within the first four days of a piglet's life after birth (Weary et al., 1996; Mazzoni et al., 2018). There have been multiple innovations in farrowing technology that are driven by decreasing preweaning mortality, most common of which is supplemental heating, but can also include sloped floors and the inclusion of solid sloping walls in farrowing pens (Ekkel et al., 2003; Damm et al., 2005; Alonso-Spilsbury et al., 2007; Danholt et al., 2011; Morello et al., 2017).

Combined with simply surviving the first 4 days after birth, a piglet in production systems in the United States is also subjected to stressful events associated with processing. Tail docking, castration, ear notching and teeth resection are common practices that are tremendously painful for piglets but are largely practiced to facilitate future production needs such as; individual animal identification, removal of boar taint, or removal of tail biting incentive that leads to outbreaks in later phases (Marchant-Forde et al., 2009; Rault et al., 2011; Marchant-Forde et al., 2014; O'Connor et al., 2014; Ison et al., 2016; Viscardi et al., 2017). Recent legislation in the European Union (albeit loosely enforced), has banned some production practices for their welfare detriment such as tail docking (Council Directive, 2008); however, elsewhere in the world the trade-off between minimizing the early life welfare issue and the potential for later life welfare issues such as tail-biting outbreaks allow that this procedure continue (Hunter et al., 2001). Teeth resection, on the other hand has very limited benefit, which is mostly seen in large litters by reducing the injuries from piglet competition over the teats (Marchant-Forde et al., 2014). Given the small window of production where this issue takes place, and the ability to treat easily on a case by case basis, in many commercial farms around the world, including in the US, teeth resection is no longer practiced. Castration however, is still common and necessary to remove the potential of tainted meat, especially in the US where the use of immuno-castration remains low. There is a concerted effort to reduce pain at castration of piglets (Marchant-Forde et al., 2014), and studies have become more frequent where analgesics and anesthesia are used on the piglets to do so (Viscardi and Turner, 2018; Burkemper et al., 2020). However, the behavioral repertoire that indicates pain remains subjective, leaving more work to done. Beyond abolishing these practices altogether to remove the welfare disturbances that directly conflict with that animals affective state, natural living, basic health and functioning (Fraser, 2008) as well as the freedom from pain and discomfort (Brambell, 1965), enriching the environment of the piglet has been attempted to alleviate compromised welfare states (Backus and McGlone, 2018). The enrichment study did not find any differences in pain behaviors immediately after the procedure. However, enriched pigs did display more growth and immunological function than their unenriched counterparts (Backus and McGlone, 2018). Currently, in the pork production sector of the US, there is not a viable substitution for castration, and abolishing tail docking has producers apprehensive of the negative downstream side effects such as tail biting outbreaks. Better attention to the welfare of the piglets is an important aspect to the production system and the industry is still searching for acceptable substitutes.

The pork production sector worldwide, and in the United State especially, is built around production goals that would see the highest amount of product and throughput that any system could offer. In recent years, however, more progress has been made in taking the welfare of animals within that system into better consideration. Space is being increased for gestating and some lactating sows (in later lactation). Technology and practices to increase the survivability and welfare of piglets in lactation is being rapidly developed and tested. A more holistic approach to food animal production that includes the animal's psychological and physiological needs is being implemented and perfected by production systems as they still maintain and pursue production goals that end in a wholesome affordable product.

Figure 1.1. Sampling of animal welfare research throughout history.



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Chapter 2 - Behavioral responses of sows exposed to conventional methods or precision-technology to mitigate piglet-crushing

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ABSTRACT

A Precision Animal Management (PAM) toolset (SmartGuard; SwineTech Inc., Cedar Rapids, IA, USA) was developed to intervene piglet-crushing events using a vibration followed by electrical impulse (VIB+EI). The objective was to evaluate sow startle, coping, and nursing responses to 3 crushing-mitigation stimuli: vibration-only (VIB; n=16), VIB+EI (n=18), or conventional methods (CONV; 3 hand slaps; n=18). Sows were exposed to a piglet distress call and the ensuing impulse for 6 sessions on d 1-4, relative to farrowing. Startle-response measures included Heart Rate (HR), cortisol secretion, and behaviors from live observation. Sows were fitted with HR-monitors before each session on days 1-4. Cortisol from ear-vein blood (100 uL) was measured before sessions -1 and -6, and after sessions -2 and -6. A novel startle-index was calculated from live observations during sessions (0=silent, lie; 100=jump, bite sow) and expressed as a percent. Coping and nursing behaviors were quantified from video collected after each session, and after ear-vein blood was collected on d 5, 7, and 9, relative to farrowing. Circadian cortisol was measured using AM and PM ear-vein blood samples for days 0-4, 5, 7, and 9, relative to farrowing. A large proportion of live observations indicated that CONV-sows only sat upright after stimuli. In contrast, most VIB+EI-sows stood-up completely ($\chi2$=207.14; N=312; p<0.01), although many jumped to the upright position ($\chi2$=44.9; N=216; $p < 0.01$). Both CONV- and VIB+EI sows vocalized ($\chi2$=199.19; N=312; p<0.01), but biting was a rare occurrence. The VIB-sows had the lowest startle-index, with minimal disturbance during

sessions. The CONV- and VIB+EI-sows displayed a 31 and 50% startle index, respectively (± 2.1 SEM; $p<0.01$). There were minimal differences in HR or cortisol measures among treatments ($p>0.10$). After sessions, VIB+EI-sows had greater oral behaviors and standing durations than CONV- and VIB-sows ($p<0.05$). The CONV- and VIB+EI-sows had similar nursing and standing behaviors, which were less than VIB-sows ($p<0.05$). Cortisol measures and coping- and nursing behavior differences were not observed on d 5, 7, or 9 ($p>0.10$). These results indicated that if PAM-technology should replace conventional methods, producers are not likely to observe long-term effects on sow behaviors. The results from this experiment were used to adjust the stimuli settings for the PAM-technology on commercial sow operations to reduce jumping.
Keywords: Machine-learning; Lay-on, porcine; Welfare

INTRODUCTION

Despite the common use of farrowing stalls in North America, 1 in 10 piglet deaths result from crushing by the sow, and nearly half of those deaths occur during the first 3 d after birth Weary et al., 1996; Knauer and Hostetler, 2013). The farrowing stall is the most common technology used by North American producers to prevent death loss from crushing. There are multiple animal welfare tradeoffs with the use of farrowing stalls: less piglets suffer from crushing, but the sow's behavior repertoire is restricted during lactation (Jarvis et al., 2005; Baxter et al., 2018). Marchant et al., (2000), indicated that increased space-allowance and nonnutritive substrates alleviated sow distress and discomfort during farrowing and lactation period (Marchant et al., 2000; Jarvis et al., 2005). However, in pens with substrate, the crushing-rate was 12.1% compared to a 5.6% crushing rate in stalls (Jarvis et al., 2005). Marchant Forde et al., (2000) reported 14-17% crushing in open-barn systems compared to 8% crushing in stalls. In the U.S., over 80% of producers choose to use the standard farrowing stall as their primary toolset to prevent crushing while still managing sows at the individual level (Johnson and Marchant-Forde, 2009).

New technologies and methods were introduced to mitigate crushing by drawing the piglets away from the sow. Methods included sloped floors, solid sloped walls, and supplemental heating (Ekkel et al., 2003; Damm et al., 2005; Alonso-Spilsbury et al., 2007; Danholt et al., 2001; Morello et al., 2017). To mitigate mortality around the time of parturition, some producers use roundthe-clock specialists to observe peri-parturient challenges (White et al., 1996). This method of increased human intervention decreased stillborn and mortality rates (White et al., 1996). Nonetheless, many U.S. producers have a 1:250 or 1:500 human:sow ratio, which limits efficient individual care at farrowing. In addition, intense operations face high turnover rates for labor, which influences variation in animal-caretaker's experience and temperament (Deen, 2003). In the coming years, US pork production should prepare for mandates and production practice requirements that are driven by legislation and animal welfare similar to other nations. The US pork production sector needs alternative solutions for mitigating crushing, with or without the use of restricted housing (Directive, 2008).

Preweaning mortality may be further reduced through Precision Animal Management (PAM) technologies that incorporate machine-learning and are computer sensory-derived (Fournel et al., 2017). A PAM-technology (SmartGuard, SwineTech Inc., Cedar Rapids, IA, USA) was developed to identify a piglet distress call and stimulate the sow to stand. The stimuli were modelled from medical devices (Transcutaneous Electrical Nerve Stimulation, TENS). Crushing risk is greatest during the first 4 days relative to farrowing (Weary et al., 1996; Mazzoni et al., 2018). Therefore, the device only is attached to the sow for this period. The technology registers a distress call from a piglet compared to a recorded crushing event, and sensors determine the location and sow's structural position using deep frame learning. If the sow is lying, the technology provides a vibration (VIB) signal followed by an electrical impulse (VIB+EI; maximum values 1000 v, 1 s). The electrical impulse (EI) stimuli used in this system is an additional animal welfare tradeoff to the farrowing stall. Utilizing electrical impulses on animals is a well-documented issue in both companion and production animals (Grandin, 2017; CAWC, 2012). Weary et al., (1996), reported that if crushing occurred in 60 s or less, piglets survived, but the risk of mortality was greatest if they were trapped under the sow for 4 or more minutes. Nonetheless, the VIB+EI presents additional ethical concerns because best management practices indicate that the electric-prod should be used as a last resort (Grandin, 2017; National Pork Board, 2015). Producers that follow the "no electric-prod" guidelines are more likely to intervene piglet crushing with hands-slaps (Hutson, et al., 1992). Both hand-slaps and the manual electric prod application are dependent on the human's sensory and decision-making response. The human response is confounded by emotion (i.e., panic, frustration), impulse responses, and previous experience (Lepri et al., 2018). Therefore, a response to a sow crushing a pig has inherent subjectivity from person-to-person, whereas responses from PAM technology are more objective and efficient, and present less variability.

The conventional method (CONV; hand-slaps) may cause sows to associate aversive stimuli with humans rather than the distress call of a piglet (Hemsworth, 2003). Sows are cognitively capable of associating actions with consequences (Puppe, et al., 2007). But, the constant noise in a farrowing house may cause sows to easily habituate to distress calls. Chaple et al., (2019), in a similar production atmosphere, found that increasing noise and activity along with sow age impacts responsiveness to piglets. An additional stimuli that is sensed over all other inputs is inevitably needed. Thus, for the current study, the first objective was to evaluate the sow's startle response to the PAM-stimuli and compare it to the conventional methods (CONV; 3 hand slaps) and a control (VIB-vibration only) during play-back of a piglet distress call. The second objective was to determine if the stimuli influenced the normal behaviors of the sow within the 20 minutes after treatment and, in the 9 days after stimuli were applied.

MATERIALS AND METHODS

Animals and Housing

The experiment was conducted in October and November 2017 at Kansas State University Swine Teaching and Research Center (Manhattan, KS). Animals were housed and managed in accordance to the 'Guide for the Care and Use of Agriculture Animals in Research and Teaching' (FASS, 2010). All procedures were approved by the Kansas State University Institutional Animal Care and Use Committee (IACUC; Protocol #3913). Fifty-eight sows (DNA line 241; primiparous and multiparous; pre-farrow body weight, 246.54 ± 56.34 SD kg) were weighed and enrolled within in two blocks (Figure 1). Sows were housed in standard farrowing stalls (length 2.3 m; width 0.43 m; height 1.5 m). No substrate was provided, and it was ensured that the mild impulse was not propagated by the metal crates by a researcher. Sows were provided ad libitum feed with automated feeders (GESTAL, Jyga Technologies, St. Lambert De Lauzon, Qc, Canada) and waterers (Aqua Series, Hog Slat, Columbus, NE). After farrowing (± 0.84 d SD), sows were weighed. Feed intake was measured daily. Piglets were offered alternative heat sources via lamps, at the rear of the stall. Piglets were processed at age 1 d, on a per farrowing day basis (day 0 farrowing ± 0.74 d SD block 1; ± 0.93 d SD block 2). The sows' pre-, post-partum, and weaning weights were collected, piglets were weighed at birth, age 7 d and at weaning (age 21 ± 0.93 d SD; Table 1). The cull-rate and sow return-to-estrus day (full standing-estrus) was measured after weaning.

Treatments

At farrowing, (0 ± 0.84 days SD), sows were randomly assigned to 1 of 3 stimuli treatments (VIB, n = 16; CONV, n = 18; VIB+EI n = 18; Figure 1). On d 1 relative to farrowing, all sows had a pocket (SmartGuard wearable patches, SwineTech) fastened to the flank region below the hair line. Sows were exposed to the stimuli-treatments in 6 sessions over 4 d in the afternoon and evening (Figure 2). At the back of every other stall, a speaker was fixed (Figure 1). Sessions were applied in groups of 5-6 sows (Figure 1). Before a group-session began, the sows were in the sternal-recumbent position. The group-session began when a 16 s piglet distress call from a crush event was played over speakers (Figure 1) in loop for up to a min (4400 Hz: Figure 2). Therefore, the entire barn was treated with 5 distress calls per session. Vibration (VIB) sows had devices in their pockets that only produced one vibration stimuli to bare skin (VIB; SmartGuard vibration max 0.4 J for 1 s) synonymous to the vibration indication in any modern handheld device. The same handler applied three open hand-slaps (2 on the back and 1 on the belly, 2-3 s) during each session to the conventionally-treated (CONV) sows (Figure 2). Care was taken for the handler applying the CONV treatment to only be seen by the CONV sows, so as to not confound human interaction with the response to the PAM-stimuli. Sows treated with PAM-stimuli had the same vibration applied to the bare skin as described above for 1 s, followed by a 1-2 second pause to allow for the sow to respond, then an electrical impulse for an additional second (VIB+EI; maximum values, 1000 v, 1 s; Figure 2) to simulate action of the ‘Smartguard’ technology provided by the funding source.

Startle-Response Measures

On session-days, sows were fitted with heartrate monitors 1 hour before the first session began and the last session ended (PolarH10 heart monitors; POLAR USA, Warminster, PA; Table 1).

In addition to the heart rate measures (HR; max, min, mean), the latency of each sow's heart rate to return to the same heart rate when she was in the rest position was measured (RR, return to resting HR). If the sow never changed from the lie position to an upright position (sit, stand, jump) during a session, RR could not be measured or included in the data set.

For each session, 2 observers evaluated for the behaviors included for the startle response (Table 3). The 2 observers stood behind each group of sows and used binary scoring to record the structural-position, vocalization-type, and if any bites occurred (Table 3). The observers had greater than > 95 % inter-observer agreement (kappa statistic > 0.95) for all sessions and groups. The structural behaviors were prioritized by researchers with over 50 years of combined production swine experience, from least active to most active (lie, sit, stand, jump). The vocalization (as noted by the trained observers) type and bite were prioritized from least to most egregious (silent, grunt, bark, squeal, bite). Then a startle-index was formulated (Figure 3) so that the least active, silent sow had would score a 0, and the most active biting sow would be a 100.

Cortisol analyses

All blood samples were collected from the ear vein (100 μl; 26-gauge, 1-cc syringes with heparin) while sows were in a resting-position (lateral or sternal recumbency). Plasma was harvested after centrifugation and frozen at -20°C until analysis. Samples analyzed for circadian cortisol included collection times 0600 and 1700 on days 0, 1, 4, 5, 7 and 9, relative to farrowing (Figure 2; Table 1). Samples collected just before session 1, after session 2, and before and after session 6 were analyzed for startle-responses to stimuli. Cortisol analysis was performed using a commercially available ELISA (DetectX; Arbor Assays, Anne Arbor, MI). The intra- and inter-assay coefficients of variation were 10.4 and 12.1 %, respectively. For circadian cortisol, area under the curve (AUC) was calculated in SigmaPlot (v 13.0) using cortisol samples for farrowing (d 0) and the morning and evening (0600 h, 1700 h) on d 1, 5, 7, 9 (Table 1). Farrowing cortisol was collected after the third pig in each litter was born and used as a covariate for all other cortisol models. Cortisol for pre- and post- treatment was expressed as a percent change by subtracting the post treatment sample from the pre-treatment sample and converting to a percent scale. Similarly, for circadian cortisol, the AM sample was subtracted from the PM sample and converted to a percent.

Coping and Nursing Behaviors

Prior to sows entering farrowing, 1 camera (Points North Surveillance Inc., Auburn, ME, USA) was installed on the ceiling above every 2 crates and continuous video was collected. Twenty-minutes of video footage was sampled after each session and after the additional ear vein blood collection on d 5, 7, and 9 relative to farrowing (Figure 2; Table 1). One trained observer timestamped the 20-min videos for each sow and her litter (Table 2) using specialized software (Observer XT 11 Noldus, Leesburg VA). Additional continuous behaviors were analyzed using wearable devices (see supplementary wearable device methods).

Piglet Total Plasma Protein (TPP) and weights

Piglet total plasma protein (Reichert-Jung 0 50° Brix hand-held refractometer) was used as a nursing-quality measure in addition to duration of sow lie-lateral and nursing behaviors (Table 2). At birth, each pig was weighed, and 500 uL of umbilicus blood was stripped into a heparinized tube. All pigs were weighed on day 7 relative to farrowing and 500 uL of whole blood was collected from every other gilt via jugular-venipuncture (Table 1). Plasma was harvested after centrifugation and stored at -20°C until refractometer analysis. Each subsampled gilt's age d 0 TPP measure was subtracted from age d 7 and the percent change in TPP was calculated.

STATISTICAL ANALYSIS

For cortisol and nominal behavior data, a general linear mixed model was fit using proc GLIMMIX of SAS (v. 9.4, SAS Inst. Inc., Cary, NC, USA) with the fixed effects of time, treatment, and the interactions of treatment x time. Sow nested within treatment was included as the random effect. Production parameters of number weaned, daily feed intake, total litter weight, sow weight at weaning were analyzed using the GLIMMIX procedure of SAS with sow body weight as a covariate. Fixed effects were sow ID and parity, with treatment included as a random effect. All data was checked for normality using the Kolomogorov-Smirnov test in the UNIVARIATE procedure of SAS (v. 9.4, SAS Inst. Inc., Cary, NC, USA) and transformation of Log(10) or SquareRoot were made when necessary. Tukey-Kramer adjustment was made to account for type-1 error in detailed pairwise comparisons within a subset of data. Categorical data were subjected to chi-square analyses and results are presented as observed, expected and residual, with significance levels set at $P < 0.05$ and tendencies at $P < 0.10$.

RESULTS AND DISCUSSION

Precision Animal Management systems may help monitor and mitigate treatments at the individual level, potentially further reducing preweaning mortality (Morello et al., 2017; Fournel et al., 2017; Halachmi and Guarino, 2016). Due to these advances in technology, there now exists the ability to monitor individual sows and incite a standing response when piglets vocalize at distress levels. Besides the farrowing stall, the other popular crushing mitigation strategy available to animal caretakers in the US is round-the-clock monitoring. This method can detect piglet crushing but uses hand-slaps or other means to incite standing in sows. This approach is not sustainable and is subject to human-error and egregious handling when sows refuse to respond to initial hand slaps. The trade-off between inciting a standing response by applying electrical impulse to the sow during crushing is that human-error is eliminated and piglets are saved, but the distress from the electrical impulse may cause long-term behavioral changes that are detrimental to sow welfare. Therefore, behavioral and physiological implications are discussed herein. The use of highly prolific genetic lines cannot be overlooked as a potential for increased piglet crushing based simply on the fact of more piglets offer more opportunity for crushing (Ward et al., 2020). For the present study, 2 sows were euthanized at farrowing, for dystocia-related reasons (Figure1). Four sows were removed (Figure 1), due to technical difficulties (incorrect treatment). Thus, 52 sows were analyzed (VIB, n = 16; CONV, n = 18; VIB+EI, n = 18).

Startle-Response

Heart rate monitors potentially collect data at a high sampling rate and can provide the sympathetic nervous system response to stimuli (Fournel et al., 2017; Marchant-Forde and Marchant-Forde, 2004; Zupan et al., 2016). After the sessions in this experiment, there were no treatment, or treatment x time significant effects for most of the heart rate (HR) measures ($p >$ 0.10; Table 4). Maximum HR irrespective of treatment was 118 ± 4.33 bpm (Table 4). These maximum HR values are comparable to maximum HR (116 to 129 ± 5 bpm) for gestating and farrowing sows in stalls while they are in the stand-position (Marchant-Forde and Marchant-Forde, 2004). There was a tendency for treatment by time interaction for the minutes to return to resting heart rate (P = 0.07; Supplementary Figure 1). After session 5 and 6 CONV or VIB+EI sows, respectively, had a greater return to resting HR than the VIB sows ($p < 0.05$; Supplementary Figure 1).

Cortisol is a common biomarker to measure stress responses (Moberg and Mench, 2000). Therefore, a blood sample was collected before the first and sixth session, and after the second and sixth session. Collection was limited to just 100 uL from the ear vein to prevent disturbing the sows while they remained in the rest-position (sit or lie). From eustress or distress, the stress axis is activated within 5-20 minutes after stimuli (Moberg and Mench, 2000; Mormede et al., 2007). For this experiment, there were few treatment x time significant effects for acute cortisol responses to the treatments ($p > 0.05$; Table 5). Farrowing blood samples had the greatest cortisol concentrations. Therefore, this sample was used as a covariate for the acute cortisol response. Parturition causes a significant increase in cortisol, which is thought to help regulate inflammation (Nagel et al., 2019). However, this makes cortisol a challenging biomarker for acute stress in the perinatal period. Nonetheless, when the percent change was considered, more CONV-sows had a negative percent change than VIB+EI sows ($p < 0.01$; Table 5). The authors suspect that the CONV-sows may have mounted more of a stress-response to humans than VIB+EI sows, so by the time the blood was collected after the sessions, a negative-feedback had already occurred. VIB+EI sows had similar percent change to the VIB-only sows ($p > 0.10$; Table 5). Hemsworth's review (2003) of stockperson attitude and handling methods indicates that gentler handling is more neutral to the sow, but erroneous handling increases generalized fear of humans.

Behavioral measures are more precise and accurate at evaluating stress responses than cortisol measures in the perinatal period. For the current project, the startle-index (Figure 3) quantified the severity of responses to the stimuli on a 0-100 scale. A startle-index of 0 indicated that the sow stayed in the lying position and remained silent during the session, whereas a startle-index of 100 represents a sow that jumped, grunted, barked, squealed, and bit during a session.

There were no time or treatment by time interactions for startle index ($p > 0.10$). Thus, the number of observations for single behaviors were also examined. Following the distress call playback, most VIB-sows remained in the lie-position (Figure 4) and did not vocalize (Figure 5; Table 6), resulting in a low startle-index (Figure 3; $p < 0.01$). This finding also confirmed research that sows are not responsive to piglet distress calls (Daigle, 2018). In addition, this indicates that the PAM-technology will not likely disturb neighboring sows versus those that are treated for piglet crushing. However, Chaple et al., (2019), outlines a changing spectrum of sow response based on environmental noise and sow age, so more sow numbers are likely needed for definitive results.

Conventional methods included 3 hand slaps to the hind quarters of the sow. A significant portion of the CONV-sows only sat up after treatment (Figure 4), although most of them vocalized (Figure 5; Table 6). Sitting is not a desired outcome because if the piglet is crushed by the hindquarters, it would not be freed if the sow simply sat up. A large proportion of CONV-sows barked after the hand slaps (Figure 5; Table 6). The sitting and bark response attributed a startle index that was 30% greater than VIB-sows. A sitting response poses a challenge for conventional sows because the manager would need to use more force to make the sow stand completely, or risk piglet welfare, in the event a piglet crushed by a sow's hindquarters.

The PAM-technology's stimuli was more effective than CONV-methods; most VIB+EI sows were in the upright, standing position after each session (Figure 4). Nonetheless, VIB+EI-sows had a 1.5-fold greater startle index than CONV-sows ($p < 0.01$; Figure 3). The VIB+EI sow startle-indexes were in the stand-jump range (Figure 3), whereas, CONV-sows were in the sit-stand range. Biting was measured over concern that sows might retaliate against piglets after the electrical impulse. Biting was a rare occurrence for this experiment (Table 6).

Jumping is also undesired because the sow may injure herself or her piglets. This challenge may be overcome because PAM-technologies can gather data from sensors and process the information for an individual animal (Fournel et al., 2017; Halachmi and Guarino, 2016). Thus, each sow’s primary response data could be used by the machine-learning software to adjust the electrical impulse during a subsequent crush-event.

For the current project, the authors noted that two multiparous, VIB-EI sows stood up before the stimulus was applied. This may indicate that these sows associate the distress call or vibration with the previous electrical impulse treatment. Future research is needed to determine the learning curve of each sow and chance-response percentage associated with PAM-technologies. On the other hand, 1 sow had a vocal response (squeal) but not a postural change during any of the VIB+EI sessions. Lameness can be found in up to 16% of sows (Heinonen et al., 2013), but the veterinarian did not observe clinical signs of sickness or injury. She was, however, in the top 10 percentile body weight for all the sows in the project (mean BW 246.5 kg), weighing 266.4 kg. Sow size relative to the stall may have influenced motivation to respond with postural changes to the PAM-stimuli. Therefore, body weight was considered as a covariate in all models but removed due to lack of significance ($p > 0.10$). A postural change to aversive stimuli indicates that the sow is using coping mechanisms to control her environment [Daigle, 2018; Koolhaas et al., 1999). The non-standing response to a primary VIB+EI-stimuli may be used as a method to identify sow health and compromised psychological welfare.

The use of electrical impulse is a hotly debated topic and offers immediate and large pushback from the public in both companion and production animals (Grandin, 2007; CAWC, 2012). By measuring the responses of sows treated with all 3 levels, direct comparisons can be made between treatments with the goal of eliminating the distress of a piglet which is being crushed. This does not excuse the fact that the sow is subject to the aversiveness of electric impulse. This impulse driven by the technology should be minimized and controlled per animal welfare councils worldwide (CAWC, 2012). In the instance of the current technology, the PAM-settings can be adjusted to stop any electrical impulses after three unsuccessful applications and provide an alert for the animal caretaker. The ability of sows to learn from the vibration stimulus in a Pavlovian manner is not out of the questions (Puppe et al., 2007). Thus, mitigating the impulse in subsequent farrowing's is possible with the vibration of the device alone. However, affecting sow position with vibration alone may not be learned until subsequent lactations. Lactation is arguably the most important phase of swine production as numbers such as 13.9 pigs born per litter and mortality of 17.5 % (Stalder, 2017), have direct impact on the rest of the production system. Assuming sows can be trained to respect the vibration of PAM-technology and relieve a pig of crushing, mortality may decrease, but opportunity for training is somewhat sparse in production systems. At 2.3 litters per sow per year of 13.9 piglets (Stalder, 2017), and an estimated mortality due to crushing alone of 20 % (estimated by 80 % crushing of the 25 % total mortality (Knauer and Hostetler, 2013; Alonso-Spilsbury et al., 2007), 2.78 piglets per litter are crushed. At 2.3 litters per sow per year, this gives each sow 6.4 estimated incidences of crushing per year which she would be subject to the PAM-technology. For the scope of this project, the impulse was under complete control by a remote in the hands of a researcher. Not identical to the product that will be marketed and available for producers. Future work is needed to analyze responses of sows to the commercially available product in large production systems.

Coping Responses

In addition to evaluating the acute stress response, the authors examined cortisol circadian function from the morning and evening samples throughout the experiment [Moberg and Mench, 2000; Mormede et al., 2007) Circadian cortisol revealed few differences between the cortisol response of sows treated with VIB-, CONV-, or VIB+EI-stimulus over the total experimental timeline (Table 5). A treatment by time interaction was observed for circadian cortisol measures (Supplementary Figure 2; $p < 0.05$). Sows among each treatment had varied cortisol concentrations. But there was no indication of significant differences for treatment within day (Tukey's adjustment LS-means $p > 0.10$). The performance axiom was also considered because deviations in feed intake and bodyweight maintenance may be indicators of chronic stress (Curtis, 2007). For this experiment, no treatment or treatment by time interactions were observed for feed intake ($p > 0.10$; Table 9). In addition, sow body weight and return-to-estrus rates did not detect differences between treatments ($p > 0.10$; Table 9).

Sows in farrowing stalls are least limited in oral behaviors. Non-nutritive oral behaviors (NNOB) can be viewed as exploratory and coping behaviors that are stereotypically observed in sows in many housing environments (Koolhaas et al., 1999). Coping behaviors can become abnormally expressed (too much or too little). Therefore, NNOB provide a direct measurement of animal welfare. For this project, desired behaviors included NNOB directed at the floor, stall, and feeder because these are precursors to nutritive behaviors such as eat and drink (Hulbert and McGlone, 2006). Undesired behaviors were those NNOB directed at the piglets, over concern that this potentially leads to savaging (Jarvis et al., 2001). The observation time in the present study was not long enough to determine if NNOB behaviors should be defined as stereotypic. Thus, the only negative NNOB behavior was piglet directed. In addition to duration of these behaviors, latency can provide insight into desired behaviors. The authors considered a short latency to perform NNOB desired because the opposite of this behavior indicates a freezing or fear response (Horback, 2017). Sows spent more time performing NNOB behaviors directed at floor and stall, as well as a difference in the total amount of NNOB behavior ($p < 0.05$, Figure 6; Table 7). These findings in conjunction with the startle-response confirm that the stimuli cause an acute behavioral response which garners more activity of the sow immediately after treatment. This activity, however, should be taken cautiously as its benefit or detriment to sow welfare is yet to be defined. The same observation protocol was applied on d 5,7, and 9 relative to farrowing to determine if treatment differences existed after sessions. There were not any behavioral differences among treatments on days 5, 7, and 9 ($p > 0.10$; Supplementary tables 1 and 2). The authors also considered the behaviors throughout the day, therefore, a wearable device that tracks any head movement (correlated with NNOB) and an accelerometer that detects sow standing was applied (Supplementary materials). The continuous data were analyzed for 20, 60 min and 20 h after sessions and days 5, 7, and 9. Only the 20-minute interval for the head-movement was significant ($p < 0.05$; Supplementary Table 3), which matched the video observations for NNOB. No additional conclusions could be gathered from these results.

Given the limitation of confinement among sows in farrowing stalls, these increased NNOB behaviors may result in sows eating more feed, but more definitive results with larger sow numbers are needed. After the sessions, sows in VIB+EI and CONV treatments had a shorter latency to eat than the VIB treated sows ($p < 0.05$; Figure 8, Table 8). Postpartum, the sow requires more monitoring of oral behaviors because lactation requires high amounts of nutrient intake (Cools et al., 2014). Sows in farrowing stalls often display anorexia and lose conditioning if they are not closely monitored (Daigle, 2018; Strathe et al., 2017). Hence, the authors suggest that any oral behaviors related to water and feed intake may benefit the sow during farrowing. Feed intake was not different among treatments in the current experiment (Table 9). These authors suspect that the NNOB-coping behaviors may translate into increased feed intake if the technology were used on a larger sample size.

Nursing Quality

Stressors during lactation are a known cause of unsuccessful nursing and increased morbidity in piglets (Von Borell, et al., 2007). A main concern over the PAM-stimuli is that it may negatively impact nursing behaviors and subsequently influence the piglets. Therefore, nursing behaviors after the treatment sessions were evaluated as well as on days 5, 7 and 9 relative to farrowing. After treatment session, VIB-sows had the least latency to start nursing, while CONV- and VIB+EI sows had similar latencies to start nursing (p = 0.01; Table 8; Figure 8). Likewise, duration for nursing at least 1 piglet was greatest among VIB-sows (p < 0.05; Figure 9). This finding was not surprising because most VIB-sows remained in a resting position during the administration of stimuli. This difference was not observed after blood was sampled from ear veins on in days 5,7,9 relative to farrowing (Treatment x Time and Treatment p > 0.10; Supplementary Table 1). All sows spent more time nursing 5 or more piglets on day 7 compared to days 5 and 9 relative to farrowing (p < 0.05; Supplementary Table 1). The authors suspect that this difference was due either to the increased human-time in the barn for piglet bodyweight and blood collection, or to a common observation that the number of nursing-bouts decrease each day after farrowing (Pajor et al., 2002).

In addition to measuring nursing behaviors, total plasma protein (TPP) and piglet performance measures were assessed. Total plasma protein is an indirect measure of IgG that is acquired from colostrum. In addition, colostrum quality and intake decrease piglet's risk of mortality and enteritis, and increases weight gain (Ison et al., 2017; Hasan et al., 2019;

Grzeskowiak et al., 2020). For this experiment, there were no differences in percent change of TPP among treatments, (p > 0.10; Table 9). Piglet performance numbers (Table 9) were consistent with the standard numbers for commercial systems in the midwestern United States (Neill et al., 2010). No differences in piglet performance, mortality, and morbidity were observed in this experiment (p > 0.10; Table 9). More data are needed at the commercial level to determine if PAM-technology will influence piglet performance. Nonetheless, nursing outcomes on the same days sows were treated with stimuli were the same in CONV-sows as VIB+EI sows.

CONCLUSIONS AND IMPLICATIONS

Pre-weaning mortality varies between 8 and 25% in systems using farrowing stalls (Knauer and Hostetler, 2013; Alonso-Spilsbury et al., 2007; Stalder, 2017) with up to 70-80% of those losses due to crushing (Alonso-Spilsbury et al., 2007). A logical mitigation of these losses beyond current practices can be PAM. The VIB+EI stimulation was the most effective at motivating the sows to stand, although some did so with a more startled response. However, the average response was still below 60% on the startle scale. If accelerometers are used to detect jumping, this added input into the PAM-technology could be used to further adjust impulse levels based on individual sow responses. This is in contrast to conventional methods, where the human-to-sow ratio in a commercial system reduces the likelihood of treating sows on an individual basis. For this experiment, coping and nursing behaviors were influenced just after treatment sessions. The main difference observed between CONV and VIB+EI sows was that the PAM-stimuli increased NNOB after treatment sessions. Producers may observe increased feeding behaviors because NNOB may transgress into significant increased feed intake in the first few days after farrowing, when sows appear least motivated to eat. However, a concern is that NNOB-can be abnormally expressed. For this experiment, the changes in NNOB were observed in the days following the last treatment session.

In the US over 80% of swine producers currently use the standard farrowing stall (Johnson and Marchant-Forde, 2009). Apart from the farrowing stall only, methods to prevent crushing included sloped floors, solid sloped walls, and supplemental heating to motivate piglets to spend non-nursing time away from the sow (Ekkel et al., 2003; Damm et al., 2005; Alonso-Spilsbury et al., 2007; Danholt et al., 2001; Morello et al., 2017). This PAM-technology may greatly decrease the crushing rate in addition to these housing modifications. Using PAM in place of humans to mitigate crushing may be beneficial to long-term wellbeing of sows because they are treated at the individual animal level. Nonetheless, a more accepted animal welfare improvement for the sow would be a housing system that does not restrict her movement. This PAM-technology has the potential to mitigate piglet crushing in a pen-system, rather than the farrowing stall system. Pen-systems were examined to increase space-allowance and add non-nutritive substrates to promote NNOB during farrowing and lactation-period (Jarvis et al., 2005; Marchant et al., 2000). However, crushing rate was over 2 times greater among sows in pens with substrate than sows in traditional farrowing stalls (Jarvis et al., 2005).

When open-barn housing was evaluated, crushing rate among open-housed sows was also over 2 times greater than farrowing stalls (Marchant et al., 2000). The creators of this PAM-technology have seriously considered the technology for sows that are not restricted by movement. They found that the current limitation is that every housing system of the less than 20% of total housing systems using loose farrowing differ greatly among systems. The PAM-technology would need to be enhanced on a case-by-case basis, which currently is not feasible for one company with limited resources. Therefore, research (and funding for research) investigating the behavioral responses in pen-housed sows needs consideration to create a homogenous, effective system at the pre-competitive level.

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Table 2.1. Summary of measures for sows. Sows treated with vibration-only (VIB, n = 16), conventional hand-slaps (CONV, n = 18), or vibration and Electrical Impulse (VIB+EI, n = 18).

Behavior or physiological variable	Time frame				
	Farrowing[1]	Startle-Response[2]	Coping Response[3]	Long-term changes[4]	Note
Heart Rate		✓	✓		Belts fastened 1 h before the first session to 1 h after the last session
Cortisol Stress Response	✓*	✓			Sampling limited to d 1 and d 4
Circadian Cortisol	✓*			✓	Sampled at morning and evening for d 1,4,5,7,9
Live Observation		✓			
Video Observation			✓	✓	20 min after each session and after blood collection on d 5,7,9
Piglet Total Serum Protein	✓			✓	Sampled 3 per sow on d 7
Piglet Body Weight	✓			✓	In addition, bodyweight at weaning
Sow Feed Intake	✓	✓	✓	✓	At weaning ADFI
Sow Body Weight	✓✓			✓	Before and after farrowing and at weaning
Sow Cull or Estrus Day				✓	Culled or return to estrus after weaning

*Used as covariate in model.
[1] Farrowing includes the time from the sow expelling the first piglet to the last.
[2] Startle-Response indicates the immediate response of sows following treatment by VIB, CONV or VIB+EI during sessions 1-6 on days 1 – 4 post farrowing.
[3] Coping-Response indicates the time period in the 20 minutes immediately post treatment of VIB, CONV or VIB+EI during sessions 1-6 on days 1 – 4 post farrowing.
[4]Longterm changes indicate behaviors or physiological parameters taken on days 5,7 and 9 relative to farrowing, or at conclusion of lactation period.
✓ Indicates at what timeframe (top) each measure (left) was collected.

Table 2.2. Live behavioral observations included in the novel startle index. During a piglet distress call play back, sows were stimulated with vibration-only (VIB, n = 16), conventional hand-slaps (CONV, n = 18), or vibration and electrical impulse (VIB+EI, n = 18). Behaviors were analyzed during 6 sessions (live observation).

Behaviors	Description
Body-Structure	
Sit	Only front legs in upright position
Stand	All legs supporting sow
Jump	Sudden propulsive action to standing
Vocalizations	
Grunt	Short-duration, low frequency (< 1 second) burst of noise
Squeal	High pitched scream, > 1 second
Bark	A short sudden loud burst of noise at a lower pitch than squeal
Bite	A sudden snap of mouth, without audible sound

Live observers recorded frequency just after a group of 5-6 sows were exposed to piglet distress call and their respective treatment and used in calculation of the startle index.

Table 2.3. Ethogram. During a piglet distress call play back, sows were stimulated with vibration-only (VIB, n = 16), conventional hand-slaps (CONV, n = 18), or vibration and electrical impulse (VIB+EI, n = 18). Behaviors were analyzed during sessions (live observation), 20 min after sessions (video), and 20 min after ear vein blood was collected on days 5,7, and 9 relative to farrowing (0).

Behaviors	Description
Oral behaviors	
Headstill	Sow's head remains immobile
[1]Non-nutritive	
Floor	Directed at floor
Stall	Directed at stall
Feeder	Directed at Feeder, not eating
Piglets	Directed at piglets
[1]Nutritive	
Eat	Sow's head in the feeder with locomotion
Drink	Sow's snout and mouth on water nipple
Body-Structure	
Sit	Only front legs in upright position
Stand	All legs supporting sow
Jump	Sudden propulsive action to standing
Lie Sternal	Sow lying on her stomach
Lie Lateral	Sow lying on her side
Nursing	
1	$\geq 1 \leq 4$ piglets manipulate udder
5+	≥ 5 manipulate the udder

[1] Behaviors timestamped from video footage for 20 minutes after each session or blood sample collection on days 5,7, and 9 relative to farrowing. Definitions adapted from Hurnik et al., 1995 and Hulbert and McGlone 2006. Sham chewing was considered, but not observed in this project.

Table 2.4. Session Heart Rate Measures. Sows were treated with vibration-only (VIB, n = 16), conventional (CONV, n = 18; 3 hand slaps), or vibration and electrical impulse (VIB+EI, n = 18) during a play back of a distress piglet call (starting point, 20 min after sessions).

	Treatment				*P*-values		
	VIB	CONV	VIB+EI	SEM	TRT	Time	TRT*Time
Heart Rate during sessions, bpm							
Mean	108.3	109.8	108.6	3.87	0.96	0.47	0.51
Max	115.1	118.2	111.6	4.33	0.54	0.75	0.34
Min	99.6	102.8	102.5	3.80	0.82	0.12	0.32
Resting	92.6	94.3	94.0	2.63	0.89	0.01	0.22
HR Return to Resting, min[1]	15.9	10.8	13.8	2.63	0.72	0.20	0.07

[1] *P* -values obtained from log(10) transformed data, LS-means derived from untransformed data.

Table 2.5. Session and Days 5, 7, 9 Cortisol Measures. Sows were treated with vibration-only (VIB, n = 16), conventional (CONV, n = 18; 3 hand slaps), or vibration and electrical impulse (VIB+EI, n = 18) during a play back of a distress piglet call. Cortisol was measured at farrowing, before session-1 and -6, and after session-2 and -6. Cortisol was also measured at 0600 and 1800 on d 1, 4, 5, 7, and 9. Farrowing-measures were used as a covariate in all models.

	Treatment				P-values		
	VIB	CONV	VIB+EI	SEM	TRT	Time	TRT*Time
Farrowing[1], ng/mL	17.7	17.6	19.0	1.13	0.59	--	--
Session[2] Response							
Before, ng/mL	20.1	17.9	17.7	1.60	0.51	0.87	0.11
After, ng/mL	20.0	18.0	20.4	2.03	0.68	0.44	0.24
Difference[3], % Δ	-22.14[a]	-88.29[a,b]	-5.50[a]	22.23	0.03	0.92	0.49
Days[4] 5, 7, 9							
Morning, ng/mL	15.4	19.6	19.9	1.96	0.21	< 0.01	0.20
Evening, ng/mL	16.2	17.5	18.3	2.27	0.80	0.74	0.83
Difference[4] ,% Δ	10.8	11.9	11.2	1.7	0.89	0.03	0.50
Circadian Cortisol[5], ng/mL	16.6	18.0	18.4	1.31	0.59	0.24	0.04
Mornings, ng/mL	17.4	20.5	20.2	1.60	0.34	< 0.01	0.41
Evenings, ng/mL	17.7	17.9	17.5	1.83	0.98	0.81	0.32
Difference[4] ,% Δ	-47.5	-32.7	-38.5	21.37	0.88	0.73	0.89
Area Under the Curve[6]	221.1	217.6	224.7	13.87	0.94	--	--

[1]Covariate for all other cortisol models; sample was collected after the third pig was born for each sow.

[2]On days 1 and 4 ± 0.84 SD relative to farrowing; before sessions 1 and 10 min after sessions 2 and 6.

[3] Δ After-sample subtracted by the before-sample then, divided by the after-sample and finally converted to percent.

[4] Δ PM-sample subtracted by the AM-sample then, divided by the AM-sample and finally converted to percent.

[5]All samples excluding the after-samples and farrowing-sample.

[6]Area Under the curve was calculated with all the samples for each sow.

Table 2.6. Startle-response Vocalization and Bite. During play-back of piglet distress, sows were treated with vibration (VIB n = 16), conventional (CONV n = 18), vibration + Electrical Impulse (VIB+EI n = 18) over 6 sessions. The number of observations are represented in the center, (expected), [residual].

	Silent		Grunt		Bark		Squeal		Bite	
VIB	**89**		**4**		**1**		**2**		**0**	
	(34.5)	[86.31]	(10.2)	[3.7]	(28.9)	[27.0]	(22.5)	[18.6]	(--)	[--]
CONV	**9**		**21**		**60**		**17**		**1**	
	(38.8)	[22.9]	(11.4)	[8.0]	(32.5)	[23.2]	(25.3)	[2.1]	(--)	[--]
VIB+EI	**14**		**8**		**33**		**51**		**2**	
	(38.8)	[15.8]	(11.4)	[1.0]	(32.5)	[0.0]	(25.3)	[30.4]	(--)	[--]

$\chi 2(6) = 239.08$, N = 312, $P \leq 0.05$.

Table 2.7. Session-Duration of Coping and Nursing Behaviors (s per 20 min observation). Over 6 sessions, sows were treated with vibration-only (VIB, n = 16), conventional (CONV, n = 18; 3 hand slaps), or vibration and electrical Impulse (VIB+EI, n = 18) during a play back of a distress piglet call (starting point).

	Treatment				*P*-values[1]		
	VIB	CONV	VIB+EI	SEM	TRT	Time	TRT*Time
n	16	18	18	--	--	--	--
Headstill	982.7[a]	950.9[a]	781.2[b]	29.20	<0.01	0.03	0.64
Oral behaviors[2]	217.3[a]	249.1[a]	418.8[b]	29.20	<0.01	0.03	0.64
NNOB[3, 4]	141.9[a]	149.4[a]	247.3[b]	20.80	<0.01	0.33	0.84
Floor	42.6[a]	53.3[a]	98.4[b]	61.60	0.01	0.06	0.95
Stall	35.6[a]	30.3[a]	68.9[b]	10.68	0.03	0.09	0.26
Feeder	17.8	9.7	20.7	5.60	0.24	0.42	0.58
Piglets	45.3	55.7	57.3	11.04	0.78	0.01	0.99
Nutritive	75.4	100.3	173.1	18.80	0.23	0.13	0.62
Eat	56.0	47.3	64.1	9.08	0.36	0.34	0.19
Drink	18.8	52.8	108.5	15.64	0.81	0.63	0.83
Upright	77.9[a]	182.0[b]	335.3[c]	30.40	0.01	0.01	0.66
Sit	39.8	67.5	76.5	16.52	0.73	0.28	0.14
Stand	38.4	112.6	256.9	32.40	0.12	0.47	1.00
Lie	1122.1[a]	1017.9[b]	862.4[b]	30.40	<0.01	0.06	0.49
Sternal[4]	463.8[a]	718.9[b]	597.2[a]	58.00	0.01	0.31	0.38
Lateral[4]	658.8[a]	299.8[b]	267.1[b]	58.80	<0.01	0.77	0.08
Nursing[5]	462.0	279.4	257.8	53.20	0.09	0.04	0.28
1 piglet	175.1[a]	91.7[b]	75.4[b]	22.36	<0.01	0.05	0.64
5+ piglets	287.1	186.6	174.62	34.80	0.09	0.33	0.22

[a,b]LS means differ $P < 0.05$; LS-means are in seconds, untransformed.

[1] Log-transformed *P*-values unless otherwise noted.

[2] Data fit a normal distribution and were not transformed.

[3] Non-nutritive behaviors directed at any object.

[4] Data were analyzed using the square root transformation to better fit normality.

[5] Nursing 1 piglet was scored when ≥ 1 but ≤ 4 piglets suckling. Nursing 5+ piglets was noted when the sow had ≥ 5 piglets suckling.

Table 2.8. Session-Latency of Coping and Nursing Behaviors (s per 20 min observation). Over 6 sessions, sows were treated with vibration-only (VIB, n = 16), conventional (CONV, n = 18; 3 hand slaps), or vibration and electrical Impulse (VIB+EI, n = 18) during a play back of a distress piglet call (starting point). If the behavior was not observed, latency could not be analyzed.

	Treatment				*P*-values[1]		
	VIB	CONV	VIB+EI	SEM	TRT	Time	TRT*Time
n	16	18	18	--			
Any oral behavior[2]	102.4	70.3	54.0	15.37	0.10	0.02	0.88
Any NNOB[3]	113.9	74.1	65.7	84.53	0.47	<0.01	0.70
Floor	215.3	202.7	167.7	27.47	0.88	0.52	0.47
Stall	263.1	146.6	167.4	32.23	0.27	<0.01	0.26
Feeder	316.7	270.9	332.9	53.61	0.40	0.81	0.29
Piglets	245.1	222.0	188.1	30.40	0.12	0.03	0.43
Any nutritive	248.7	319.2	269.9	40.03	0.10	0.01	0.09
Eat	574.0[a]	295.2[b]	302.0[b]	69.50	0.03	0.56	0.47
Drink[2]	246.6	351.5	369.3	40.03	0.13	0.84	0.34
Lie after sit or stand							
Sternal[2]	150.5	119.0	153.8	46.20	0.80	0.48	0.63
Lateral[2]	513.9	774.0	636.7	79.17	0.12	0.41	0.63
Nursing[4]							
1 piglet	375.7[a]	601.1[b]	609.8[b]	58.63	0.01	0.35	0.53
5+ piglets[5]	574.1	652.9	656.6	68.07	0.61	0.06	0.35

[a,b]LS-means differ $P < 0.05$; LS-means are in seconds, untransformed.
[1] Log-transformed *P*-values unless otherwise noted.
[2] Data were analyzed using the natural log transformation to better fit normality.
[3] Non-nutritive behaviors directed at any object.
[4] Nursing 1 piglet was scored when ≥ 1 but ≤ 4 piglets suckling. Nursing 5+ piglets was noted when the sow had ≥ 5 piglets suckling.

Table 2.9. Performance measures. Over 6 sessions, sows were treated with vibration-only (VIB, n = 16), conventional (CONV, n = 18; 3 hand slaps), or vibration and electrical Impulse (VIB+EI, n = 18) during a play back of a distress piglet call.

	Treatment				P-values		
	VIB	CONV	VIB+EI	SEM	TRT	Time	TRT*Time
n	16	18	18	--	--	--	--
Sow weight							
Enrollment, kg	248.1	243.3	245.3	6.50	0.87	-	-
Day 21, kg	221.9	222.5	221.8	5.70	1.00	-	-
Difference[1], %Δ	10.4	9.2	9.4	0.87	0.58	-	-
ADI[2], kg	5.7	5.5	5.6	0.21	0.78	-	-
Sessions[3], kg	4.0	4.1	4.3	0.21	0.57	<0.01	0.75
Days[4] 5-9,kg	5.7	5.5	5.8	0.24	0.51	<0.01	0.47
Piglets							
Born[5], no.	15	13	15	0.7	-	-	-
Weaned, no.	14	12	13	0.4	0.16	-	-
Piglet weight							
Birth[6], kg	1.3	1.4	1.3	0.05	-	-	-
Day 7, kg	2.5	2.8	2.7	0.10	0.26	-	-
Difference, %Δ	48.9	49.4	49.6	1.43	0.95		
Day 21	5.3[c]	5.8[d]	5.8[d]	0.19	0.10	-	-
Difference[7], %Δ	52.5	52.3	53.9	0.90	0.39	-	-
Overall Difference, %Δ	75.8	75.9	76.9	0.65	0.46	-	-
Total litter weaning weight	71.2	72.3	71.6	3.11	0.97	-	-
Total Plasma Protein[8], %Δ	71.7	71.7	78.0	15.14	0.84	-	-

[a,b]LS means: differ $p < 0.05$; [c,d]tend to differ $p = 0.10$

Δ Later value, subtracted by the initial value, then divided by the initial value and finally converted to percent.

[1]Enrollment to Day 21 (weaning).

[2]Average Daily Feed Intake (ADFI) from enrollment until d 21.

[3]ADFI from enrollment until the six session on d 4 relative to farrowing (d 0 ±0.84 SD).

[4]ADFI from d 5 to 9 relative to farrowing (d 0 ±0.84 SD).

[5] Piglets directly born from dam; Some cross-fostering caused sows to gain piglet(s).

[6]Birth weight was used as a covariate for all piglet weight models and the Total Plasma Protein model.

[7]d 7 to 21 relative to farrowing (d 0 ±0.84 SD).

[8]Percent change in total plasma protein (TPP) was calculated by subtracting day 0 TPP (total plasma protein) from day 7 TPP.

Figure 2.1. Experimental treatment layout. A total of 56 sows were enrolled over 2 blocks (A, October 2017; B November 2017). Three sows died due to farrowing complications. At farrowing, sows were randomly assigned 3 treatments: Vibration-only (VIB n = 16); Conventional (CONV n = 18; 3 hand slaps); Vibration + Electrical Impulse (VIB+EI n = 18). Sow data sets were excluded (X) for one VIB-sow and 3 VIB+EI due to technical issues with treatments. Every other farrowing stall had a speaker fixed on the back and a camera (90° angle) above two sows. Six session were conducted on d 1-4 relative to farrowing in groups of 6 (numbers indicate group treatment order). A distress call was played during each session on d 1-4 relative to farrowing (± 0.84 SD). Video recording was done via one camera fixed to the ceiling above every other stall.

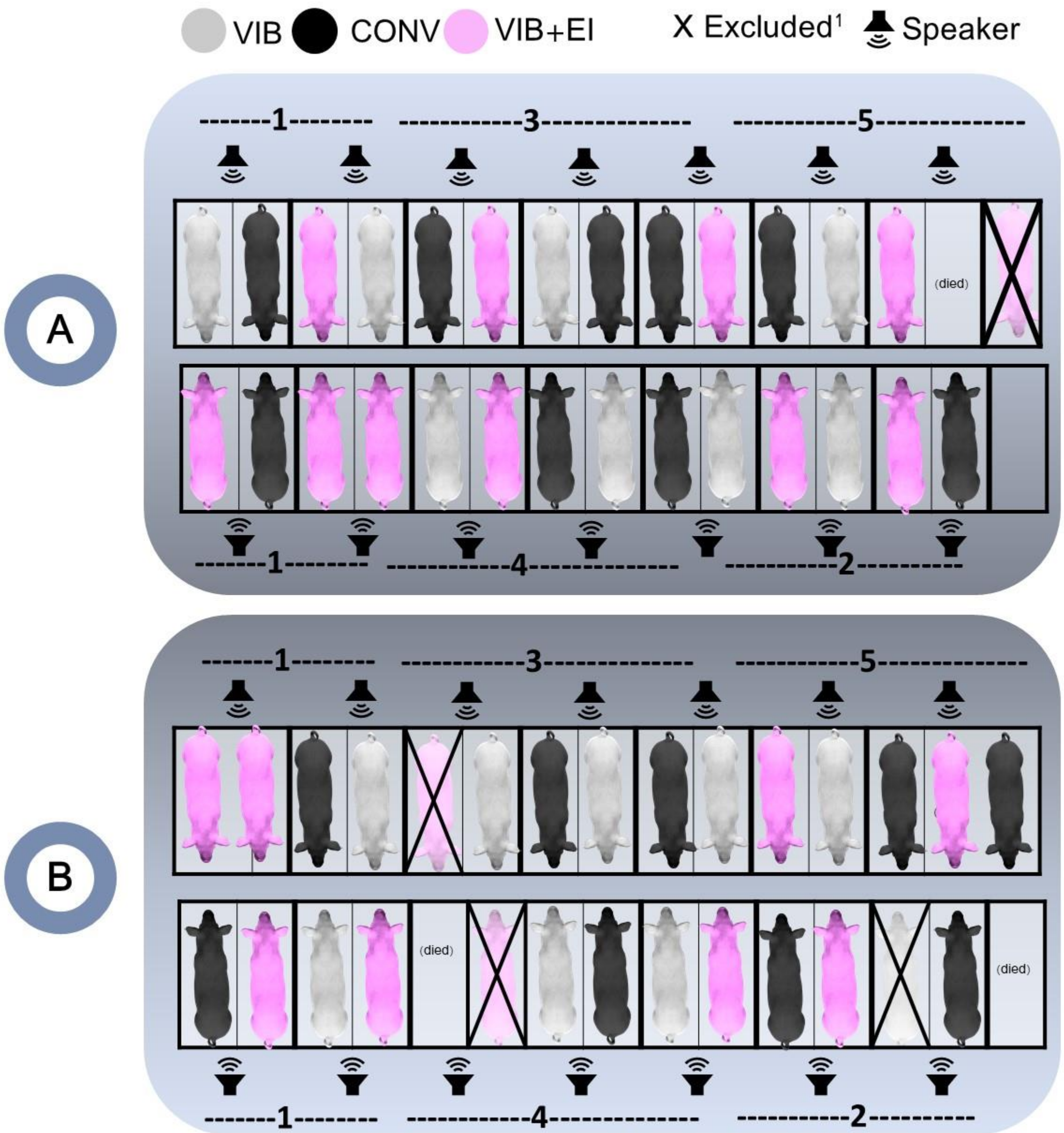


Figure 2.2. Timeline for experiment and sessions. After farrowing (d 0), 6 sessions (solid circles) were conducted. Each group of 5-6 sows within a session was treated within 30 seconds. First, a distress-call was played over the speakers on loop. Then, the devices were activated for vibration for the VIB-sows (n = 16) and VIB+EI-sows (n = 18) while three hand-slaps were applied to the CONV-sows (n = 18). Just after the vibration, an electrical impulse was applied to the VIB+EI-sows. Two observers (eye-symbol) documented structural and vocal scores for each group-session for the first 60 s after the playback began. Observers were blind to the VIB- and VIB-EI treatments, but they could not be blinded to CONV- because the same person administered 3 hand slaps. While sows were resting (sit or stand) up to 100 uL of whole blood (heparin) was collected using ear-vein venipuncture. Blood was sampled on day 0 (farrowing), in the mornings (AM) and evenings (PM) on d 1, 4, 5, 7, and 9 for circadian cortisol measures. The cortisol acute response was measured after sessions 2 and 6. Video (camera) footage was collected analyzed for -min after each session and each PM blood sample on days 5, 7, and 9.

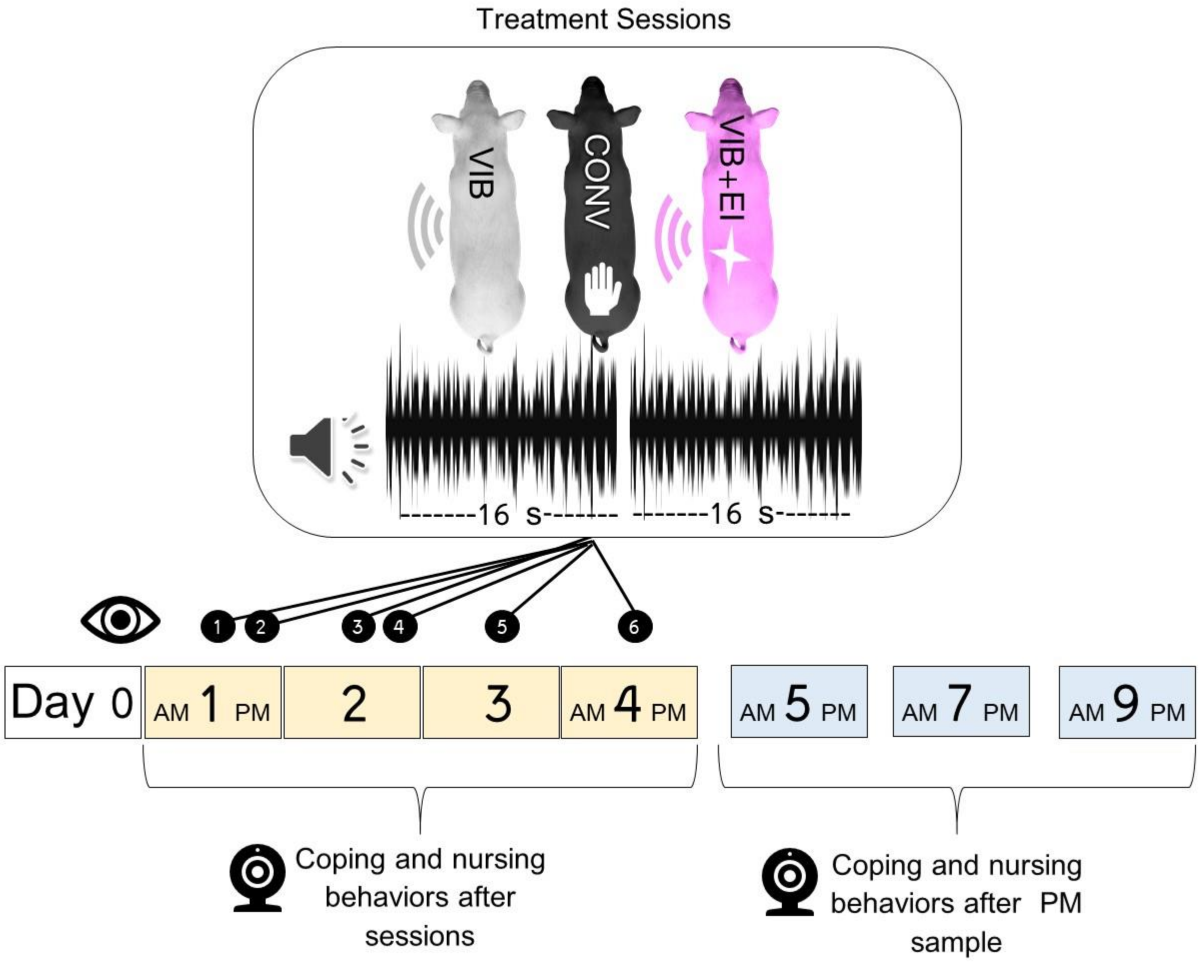

Treatment Sessions
VIB
CONV
VIB+EI
-------16 s-------
-------16 s-------
1
2
3
4
5
6
Day 0
AM 1 PM
2
3
AM 4 PM
AM 5 PM
AM 7 PM
AM 9 PM
Coping and nursing behaviors after sessions
Coping and nursing behaviors after PM sample

Figure 2.3. Right Panel: Startle index equation and representation of vocalizations and postures. Combinations of behaviors were plotted on a 0-100 scale, where 0 indicates a silent sow that remains in the lie-position and 100 represents a biting sow that jumps. The equation represents the calculation to create this scale: IF: l = lie, s = sit, S = stand, j = jump, i = silent, g = grunt, b =bark, q = squeal and, B = bite. Left Panel. Startle Index calculated from live observations immediately after play back of piglet distress call combined with a treatment of Vibration-only (VIB; n= 16), Conventional (CONV; 3 hand-slaps; n= 18), and Vibration followed by an electrical impulse (VIB+EI; n= 18). [a,b,c] LS-means differ. P-values = Treatment <0.0001; Time 0.34; Treatment *Time 0.43).

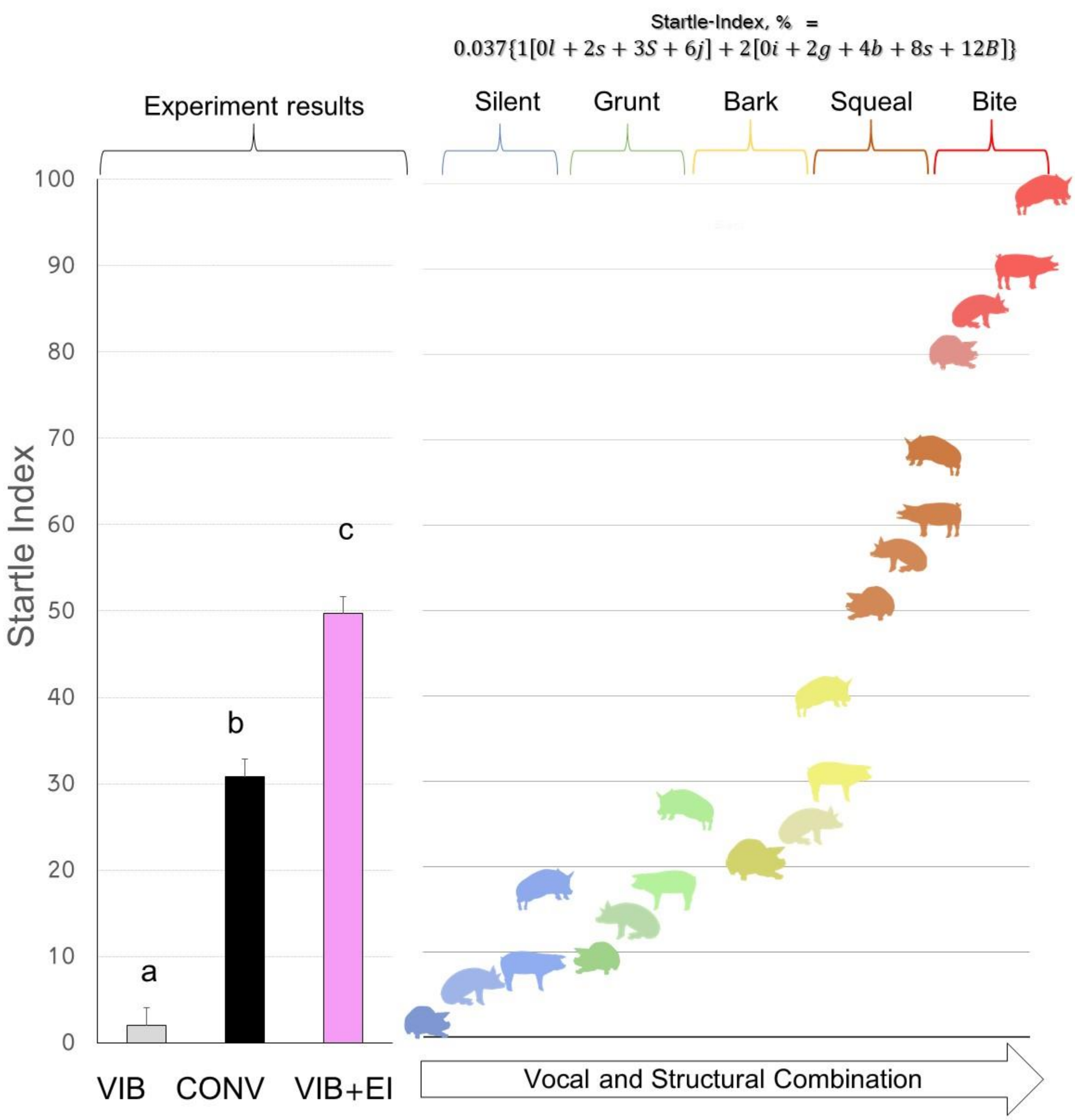


Figure 2.4. Chi-square results of structural behaviors after play-back of distress call. Sows were treated over 6 sessions with vibration-only (VIB, n = 16), conventional (CONV, n = 18; 3 hand slaps), and, vibration + electrical Impulse (VIB+EI, n = 18). The number of observations are represented in the center of the cell or silhouette, (expected), [residual].

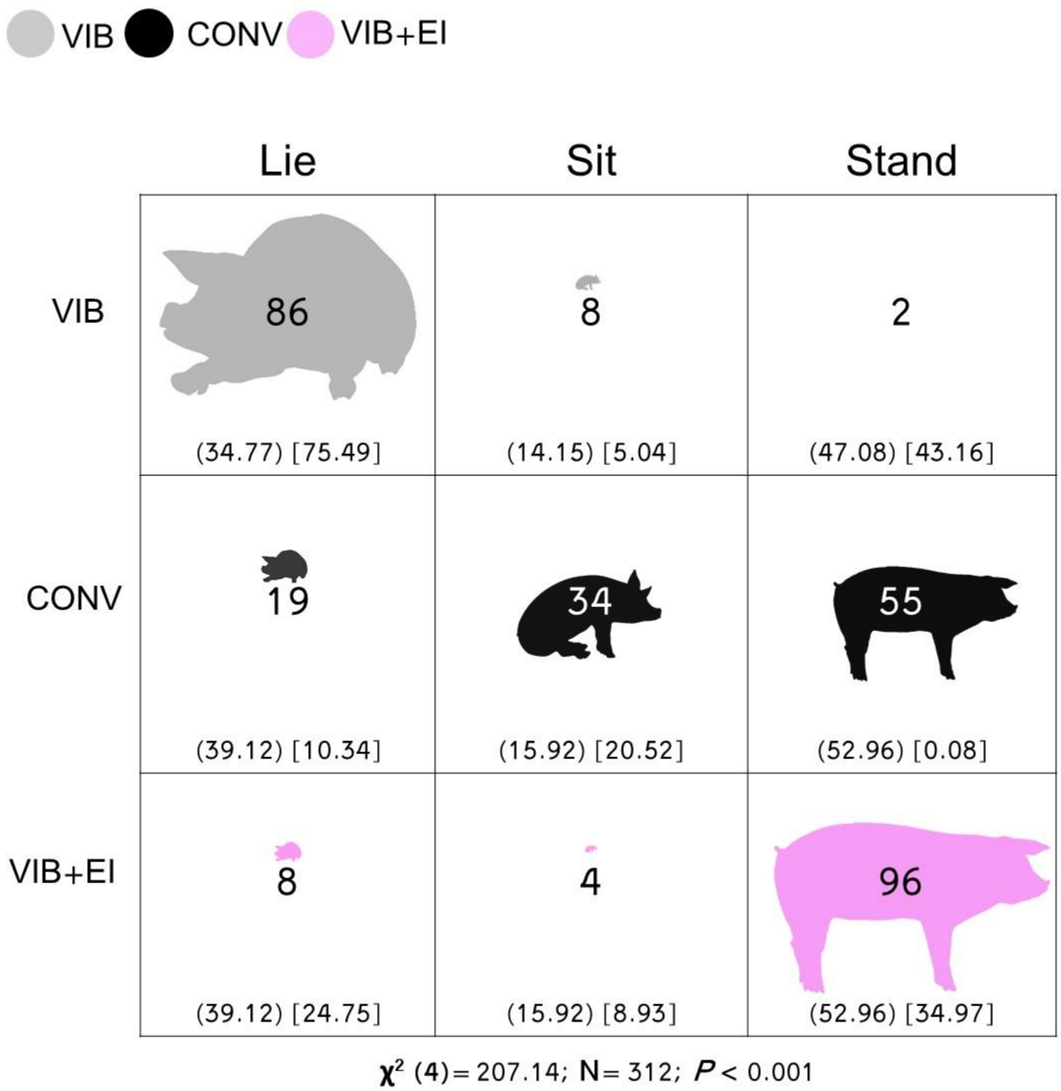


Figure 2.5. Chi-square of all vocalizations (top) and jumping (bottom) after play-back of distress call. Sows were treated with vibration-only (VIB, n = 16), conventional (CONV, n = 18; 3 hand slaps), and, vibration + electrical Impulse (VIB+EI, n = 18). No VIB-sows jumped. Therefore, the analysis was conducted for just CONV- vs. VIB+EI-sows. The number of observations are represented in the center of the cell or silhouette, (expected), [residual].

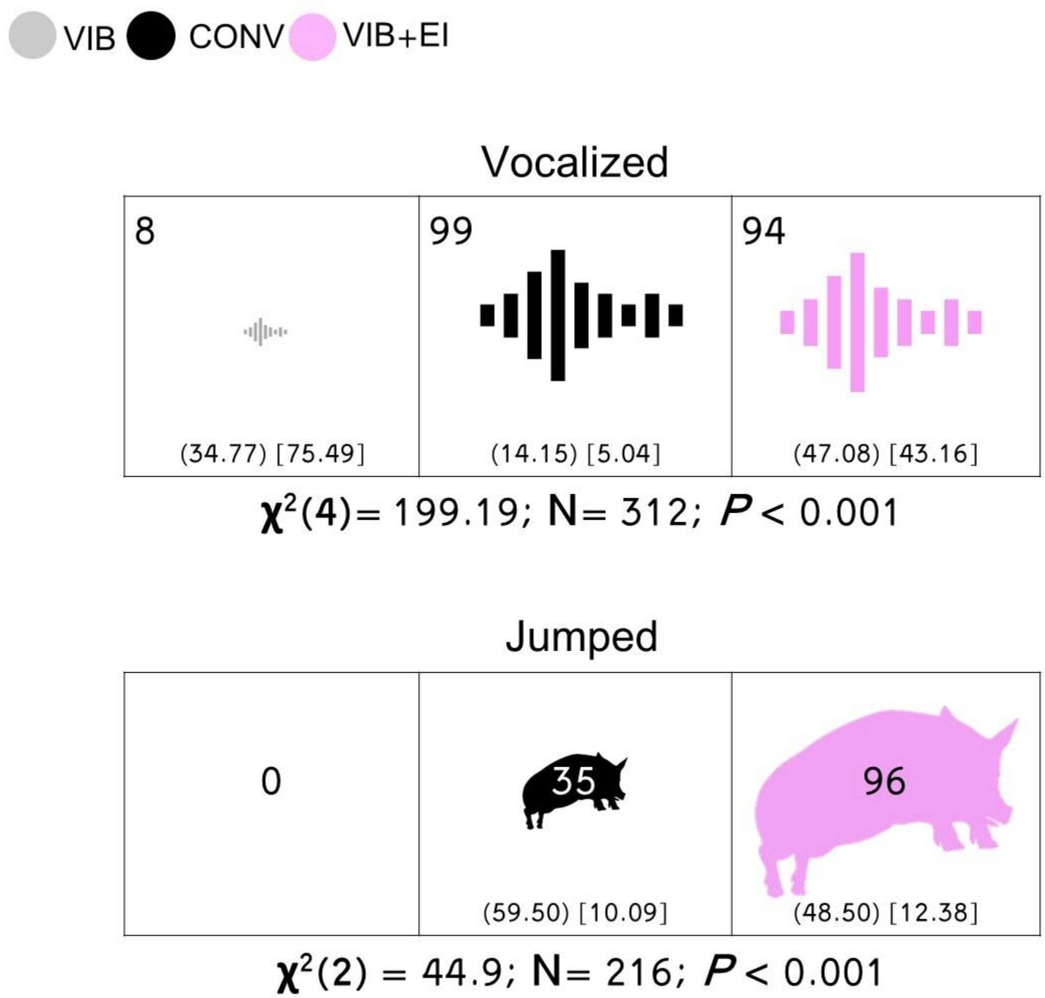


Figure 2.6. Coping behavior duration after sessions. After playback of a piglet distress call, sows were treated with vibration-only (VIB, n = 16), conventional (CONV, n = 18; 3 hand slaps), and, vibration + electrical Impulse (VIB+EI, n = 18). Twenty-minute videos were analyzed after each session. [a,b] LS means within behavior differ ($p < 0.05$). *LS means for total non-nutritive oral behaviors differ (sum of stack bars; $p < 0.05$).

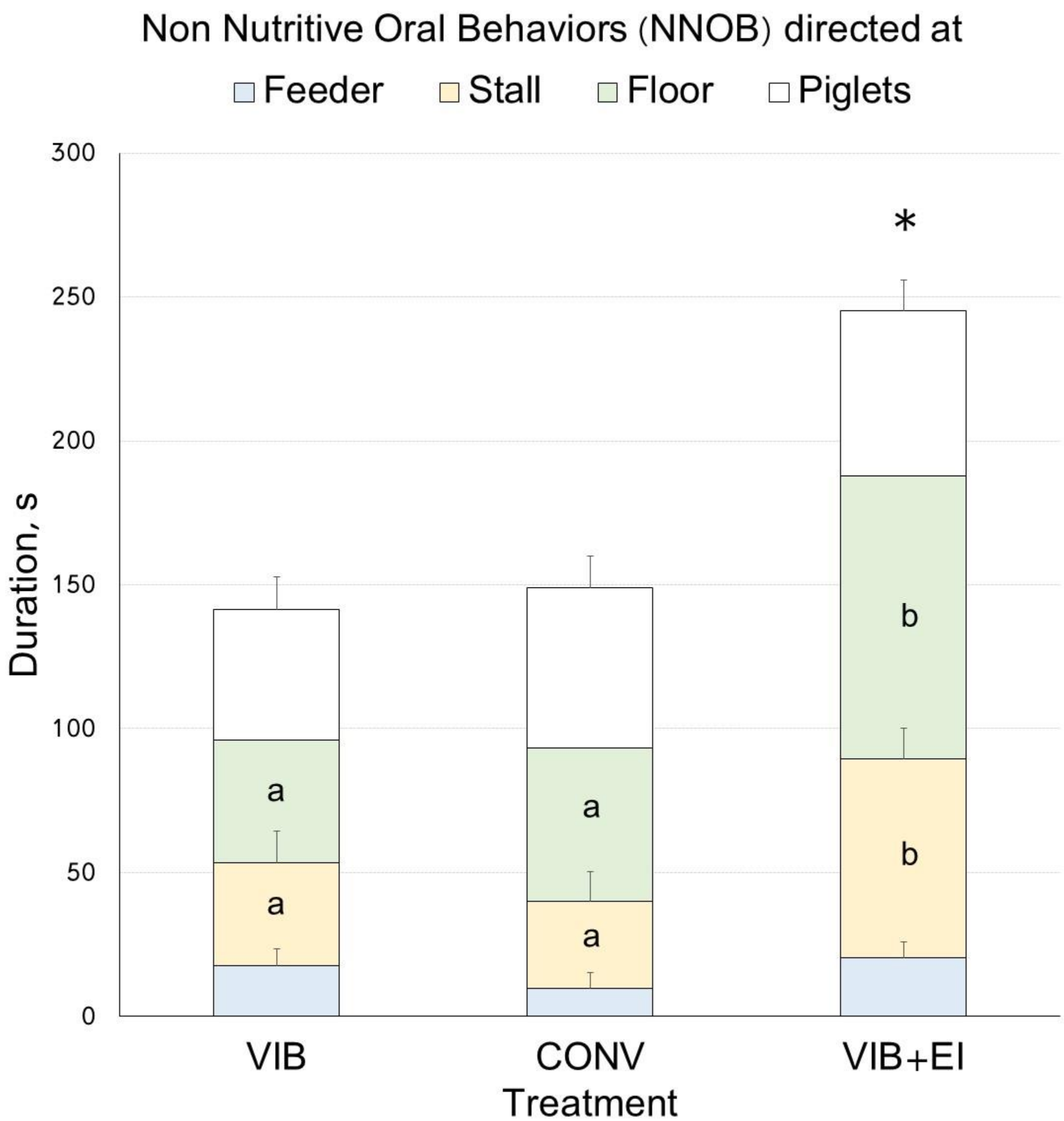


Figure 2.7. Rest behavior duration after sessions. After play-back of a piglet distress call, sows were treated with vibration-only (VIB, n = 16), conventional (CONV, n = 18; 3 hand slaps), and, vibration + electrical Impulse (VIB+EI, n = 18). Twenty-minute videos were analyzed after each session. [a,b] LS means within behavior differ ($p < 0.05$). *LS means for total lie differ (sum of stack bars; $p < 0.05$).

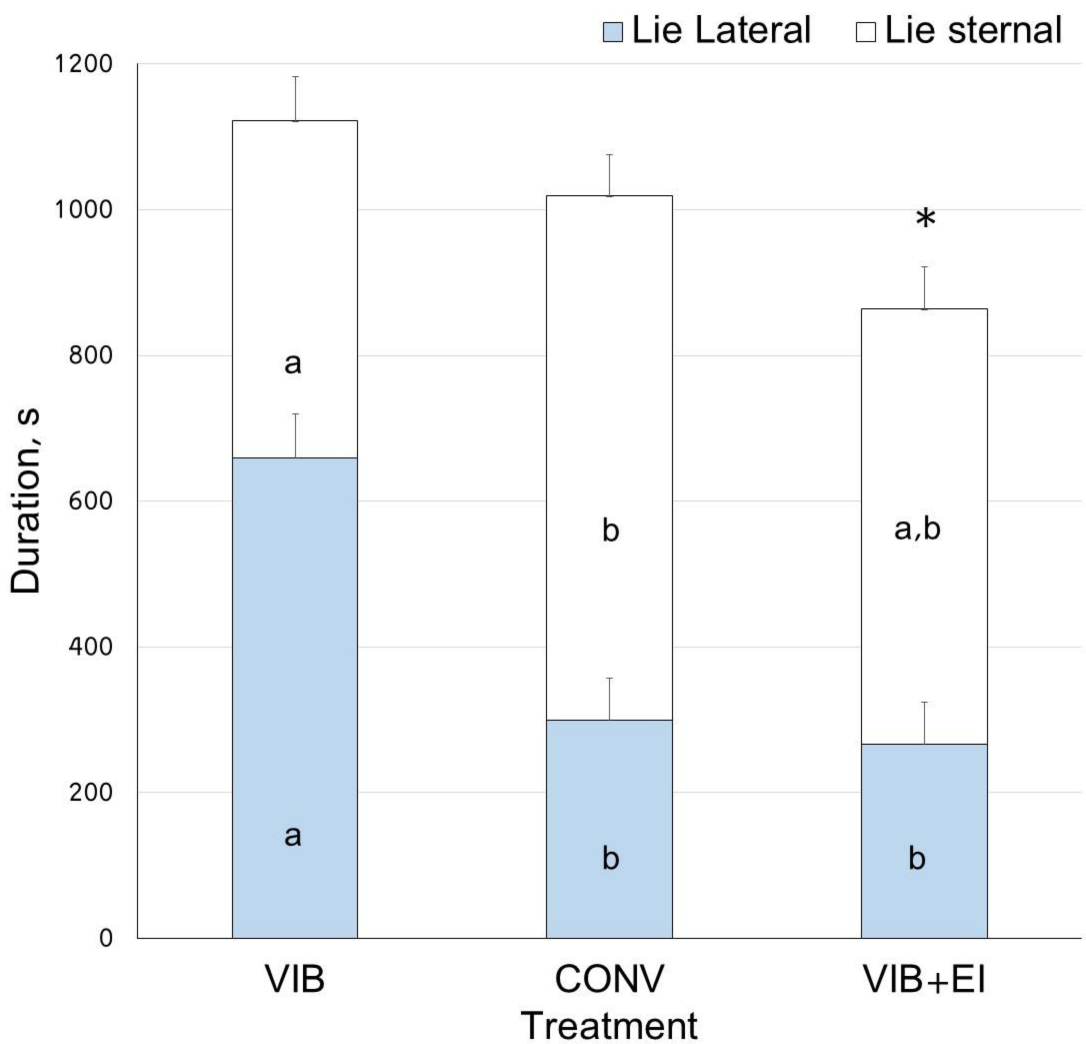


Figure 2.8. Latency to eat (top) and start a nursing bout (bottom) after sessions. After play-back of a piglet distress call, sows were treated with vibration-only (VIB, n = 16), conventional (CONV, n = 18; 3 hand slaps), and, vibration + electrical Impulse (VIB+EI, n = 18). Twenty-minute videos were analyzed after each session. [a,b] LS means within behavior differ ($p < 0.05$).

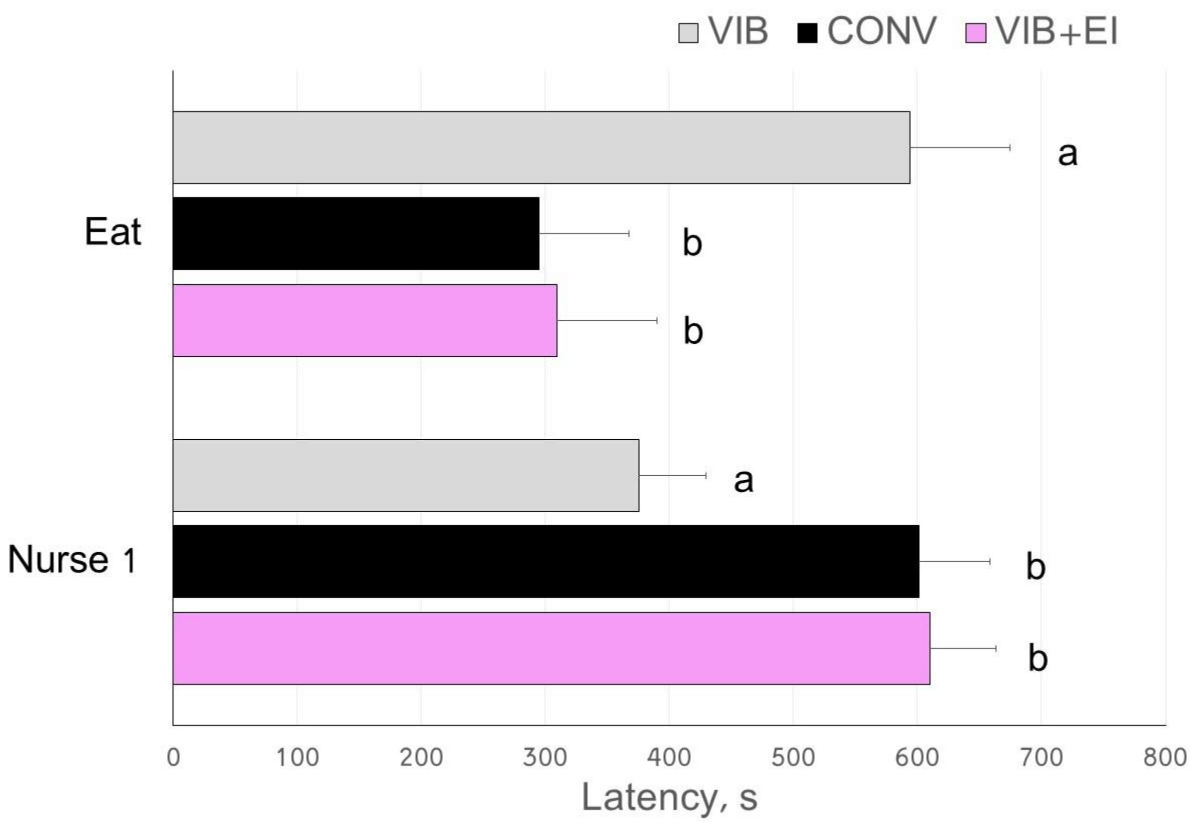
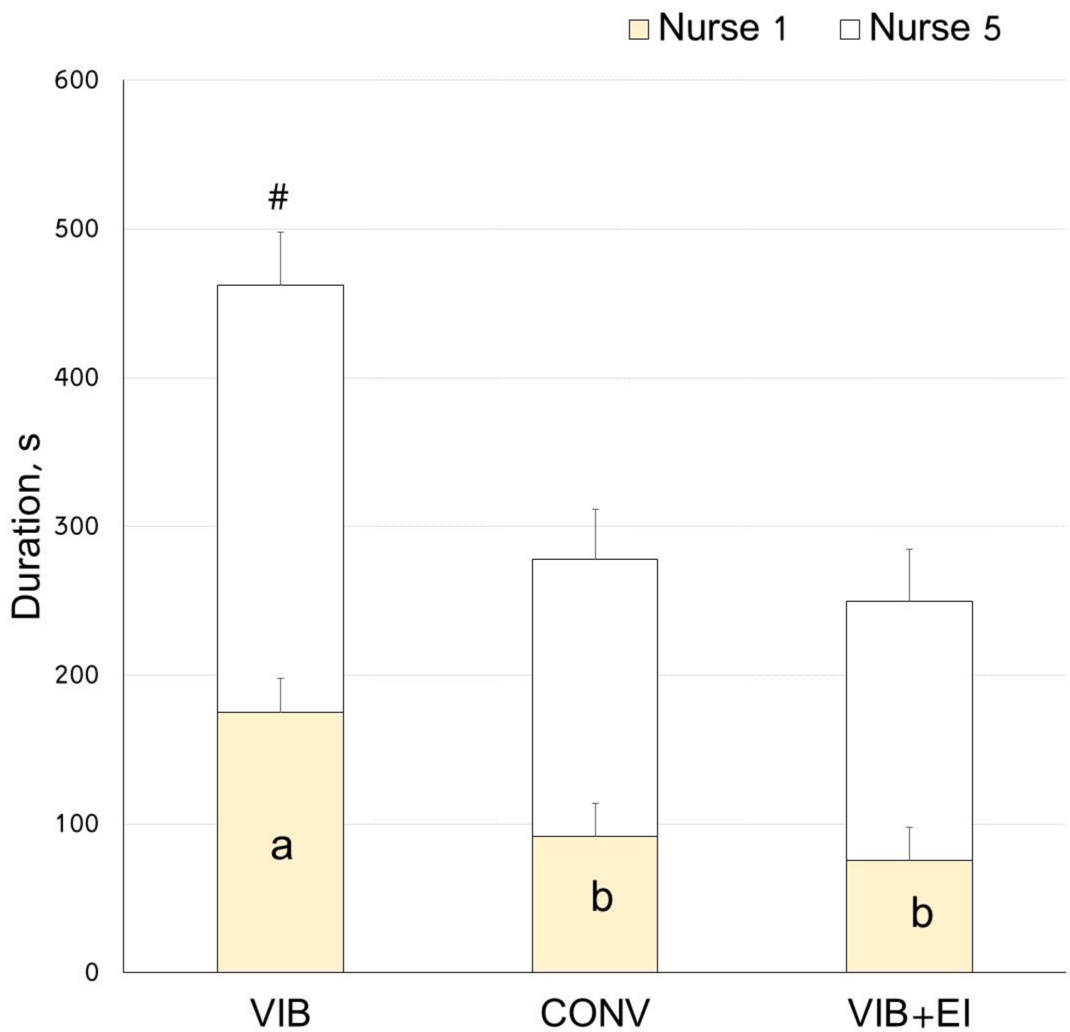


Figure 2.9. Nursing behaviors after sessions. After play-back of a piglet distress call, sows were treated with vibration-only (VIB, n = 16), conventional (CONV, n = 18; 3 hand slaps), and, vibration + electrical Impulse (VIB+EI, n = 18). Twenty-minute videos were analyzed after each session. [a,b] LS means within behavior differ ($p < 0.05$). *LS means for total lie differ (sum of stack bars; $p < 0.05$).



Supplementary Table 2.1. Duration for Days 5, 7, and 9, Coping and Nursing Behaviors. Long term coping behaviors and nursing duration (seconds). Video was sampled for 20 minutes on days 5, 7, and 9 relative to farrowing. Among sows that were treated six times over days 1+4 with vibration-only (VIB, n = 16), conventional (CONV, n = 18; 3 hand slaps), or vibration and electrical Impulse (VIB+EI, n = 18) during a play back of a distress piglet call. Starting point was after 100 uL of blood was collected from sow ear vein.

	Treatment				*P*-values[1]		
	VIB	CONV	VIB+EI	SEM	TRT	Time	TRT*Time
n	16	18	18	--			
Headstill	1045.8	1007.7	1026.8	36.00	0.76	0.12	0.50
Oral behaviors[2]	154.2	192.3	173.3	36.40	0.71	0.01	0.74
NNOB[3, 4]	46.4	93.7	65.3	17.20	0.66	0.05	0.93
Floor	23.3	41.6	28.2	9.20	0.55	0.12	0.69
Stall	4.5	8.3	10.8	35.60	0.73	0.04	0.56
Feeder	7.8	28.7	7.6	8.96	0.20	0.10	0.92
Piglets	10.8	15.2	18.6	5.12	0.65	0.85	0.10
Nutritive	107.8	98.5	107.9	26.00	0.54	0.57	0.46
Eat	58.7	65.5	54.5	24.40	0.89	0.33	0.47
Drink	49.1	33.0	53.5	8.96	0.53	0.88	0.35
Upright	84.5	129.1	90.3	32.00	0.82	0.69	0.39
Sit	13.5	23.5	15.9	8.08	0.25	0.99	0.30
Stand	71.0	105.5	74.5	29.40	0.26	0.94	0.80
Lie	543.5	476.4	504.0	39.20	0.49	0.66	0.19
Sternal[4]	184.5	237.5	206.4	41.60	0.34	0.82	0.90
Lateral[4]	359.0	238.9	297.6	44.40	0.11	0.17	0.27
Nursing[5]	572.0	594.5	605.7	47.60	0.88	0.24	0.51
1 piglet	276.4	293.1	308.7	35.60	0.80	0.01	0.98
5+ piglets	295.7	301.5	297.0	34.40	0.99	0.05	0.25

[a,b]LS means differ $P < 0.05$; LS-means are in seconds, untransformed.
[1] Log-transformed *P*-values unless otherwise noted;
[2] Data fit a normal distribution and were not transformed.
[3] Non-nutritive behaviors directed at any object.
[4] Data were analyzed using the square root transformation to better fit normality.
[5] Nursing 1 piglet was scored when ≥ 1 but ≤ 4 piglets suckling. Nursing 5+ piglets was noted when the sow had ≥ 5 piglets suckling.
[5] Nursing 1 was noted when the sow was lying laterally with ≥ 1 but ≤ 4 piglets present and manipulating the udder; nursing 5+ was noted when the sow had ≥ 5 piglets present and manipulating the udder.

Supplementary Table 2.2. Latency for Days 5, 7, and 9, Coping and Nursing Behaviors (seconds per 20 min observation). Sow were treated with vibration-only (VIB, n = 16), conventional (CONV, n = 18; 3 hand slaps), or vibration and electrical impulse (VIB+EI, n = 18) during a play back of a distress piglet call (starting point). Starting point was after 100 uL of blood was collected from sow ear vein most sows remained in the lie-position. If the behavior was not observed, latency could not be analyzed.

	Treatment				*P*-values[1]		
	VIB	CONV	VIB+EI	SEM	TRT	Time	TRT*Time
n	16	18	18	--			
Any oral behavior	260.3	289.8	276.1	45.77	0.21	0.20	0.94
NNOB[2]	289.2	294.0	283.3	44.73	0.49	0.23	0.79
Floor	302.2	348.1	413.8	47.07	0.18	0.13	0.54
Stall	487.2	555.6	389.6	52.90	0.78	0.55	0.75
Feeder	420.4	364.7	389.3	64.80	0.86	0.12	0.68
Piglets	380.1	309.2	314.3	37.40	0.76	0.41	0.76
Any Nutritive	402.4	411.3	360.9	66.47	0.96	0.01	0.94
Eat[3]	--	510.3	397.5	90.30	0.56	0.20	0.44
Drink	450.7	415.1	372.7	66.50	0.77	0.03	0.76
Lie after sit or stand							
Sternal	281.3	280.2	332.6	66.93	0.95	0.02	0.34
Lateral	390.1	401.1	421.4	49.13	0.76	0.01	0.65
Nursing[4]	226.9	226.4	197.5	47.40	0.53	0.32	0.43
1 piglet	373.3	416.8	371.2	57.03	0.66	0.10	0.98
5+ piglets	397.3	365.0	392.7	61.90	0.95	0.01	0.92

[a,b]LS means differ $P < 0.05$; LS-means are in seconds, untransformed.
[1] Log-transformed *P*-values unless otherwise noted.
[2] Non-nutritive behaviors directed at any object.
[3]P-values derived from normally distributed data (untransformed)
[4] Nursing 1 piglet was scored when ≥ 1 but ≤ 4 piglets suckling. Nursing 5+ piglets was noted when the sow had ≥ 5 piglets suckling

Supplementary Table 2.3. Automated data analyses. Before farrowing, all sows were fitted with an event sensor and logger (HOBO Pendant® Event Data Logger - UA-003-64, ONSET Computer Corp., Bourne, MA, USA) on their head or neck region by a fabric pocket fixed to the skin of the sow via 3M tape (3M, St. Paul, MN, USA). In addition, the back left leg of each sow was fitted with an accelerometer (64 k, Onset Pendant G, onset), which captured the y-axis (stand vs. lie) and the z-axis (sternal-recumbency vs. Lateral-recumbency). The head-logger was used to automate the process of capturing oral behaviors (both nutritive or non-nutritive) while the leg-logger was used to determine the lying and standing positions. The head-logger captured the occurrence of head movement within a second whereas the leg-logger provided accelerometric relative positioning within a minute. The captured data was aligned based on the treatment session timeline and aggregated to investigate effects for 20 min, 1 h, and 20 h after each session. After data were adjusted for rotation of accelerometer using python software, a generalized, linear mixed model was fitted. Fixed effects of session, treatment (VIB,CONV,VIB+EI), farrowing block (1 or 2), parity (1 – 5), and parity 1 vs. 2+ (2 - 5) are presented during the 6 sessions while considering each sow's residual effect as the model's random effect. The first 20-minutes of automated data (head-movement, lying) was compared to the available for 20m, 1h, and 20h and data were correlated.

Automated-data *P*-values, Time After Sessions						
		Treatment	Block	Parity	Parity 1 vs 2+	Transformed
Head- movement						
20 min		0.8403^{+S}	0.0003	0.6839	0.8798	Lognormal
1 h		0.8065	0.0051	0.2549	0.0906	Lognormal
20h		0.8124	0.0021	0.5290	0.1582	Lognormal
Leg-Accelerometer						
	Standing	0.1372	0.4816^{+S}	0.5474	0.4687	Lognormal
20 min	Lie Right*	0.1678	0.4972	0.5529	0.3649	Normal
	Lie Left*	0.0413^{+S}	0.2757^{+S}	0.5065	0.2454	Normal
	Standing	0.5886	0.1949	0.3781	0.6297	Lognormal
1h	Lie Right*	0.0540	0.2072	0.1377^{+S}	0.7549	Normal
	Lie Left*	0.2204	0.2642^{+S}	0.4729	0.2357	Normal
	Standing	0.5991	0.6611	0.5447	0.7388	Lognormal
20h	Lie Right	0.7587	0.3926$^{\pm S}$	0.8523^{-S}	0.3550	Normal
	Lie Left	0.8221	0.6880$^{\pm S}$	0.8356^{-S}	0.3854	Normal

$^{+S}$ The fixed effect exhibits a significant effect in combination with session ($P < 0.05$).

$^{-S}$ Session has a significant fixed effect.

$^{\pm S}$ Both $^{+S}$ and $^{-S}$ effects are observed.

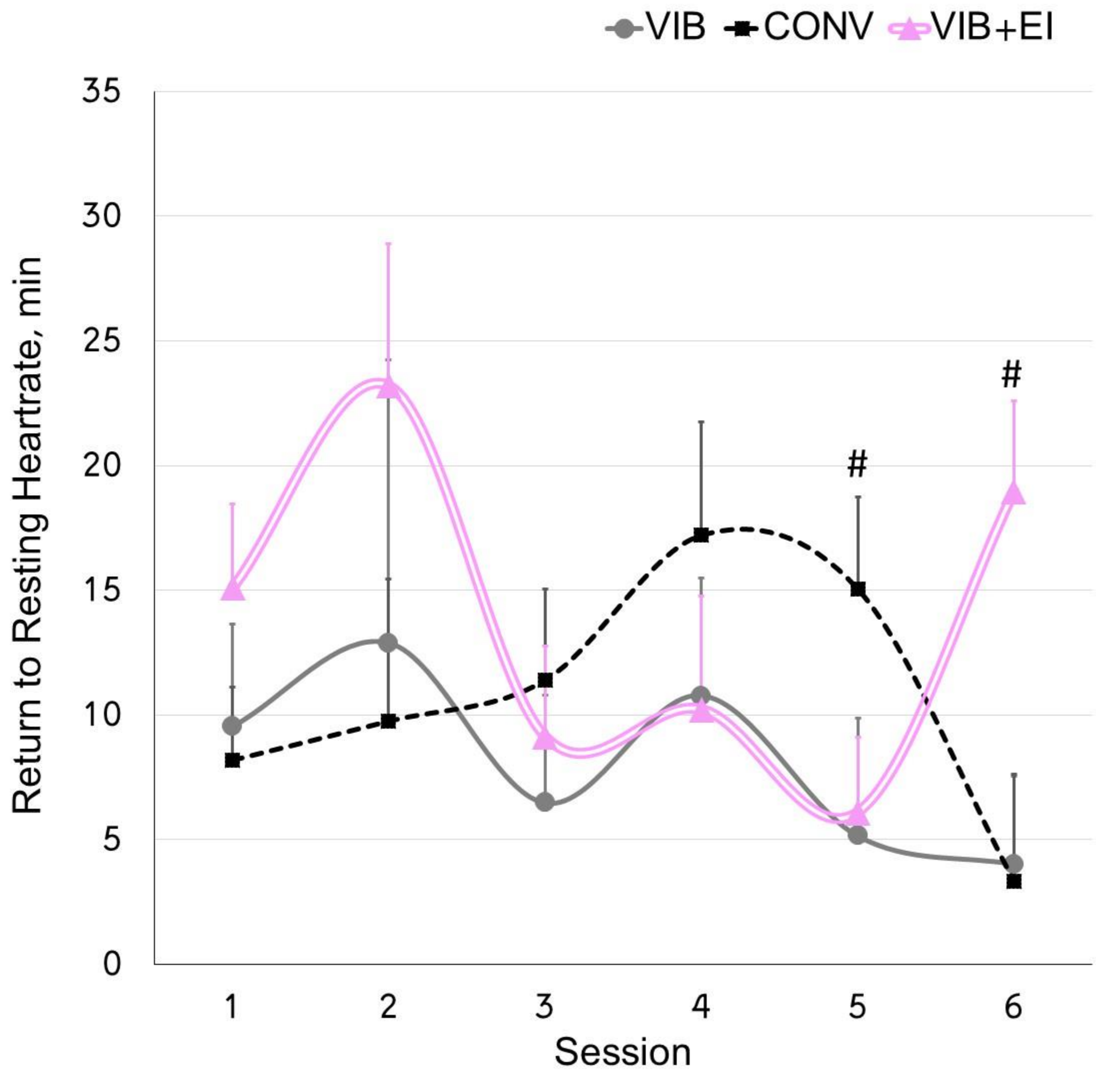
* Provided data to the model had limitation (censored and survival) for a good fit

Supplementary Table 2.4. Cull rate and Return to Estrus at 4 or 5 days. During play-back of a piglet distress sows were treated with vibration (VIB n = 16), conventional (CONV n = 18), vibration + Electrical Impulse (VIB+EI n = 18) over six sessions. Sows were culled at weaning (day 21). Remaining sows were placed into gestation stalls and serviced if they were in full estrus (lordosis). Sows either came into estrus 4 or 5 days after weaning. The number of observations are represented in the center, (expected), [residual].

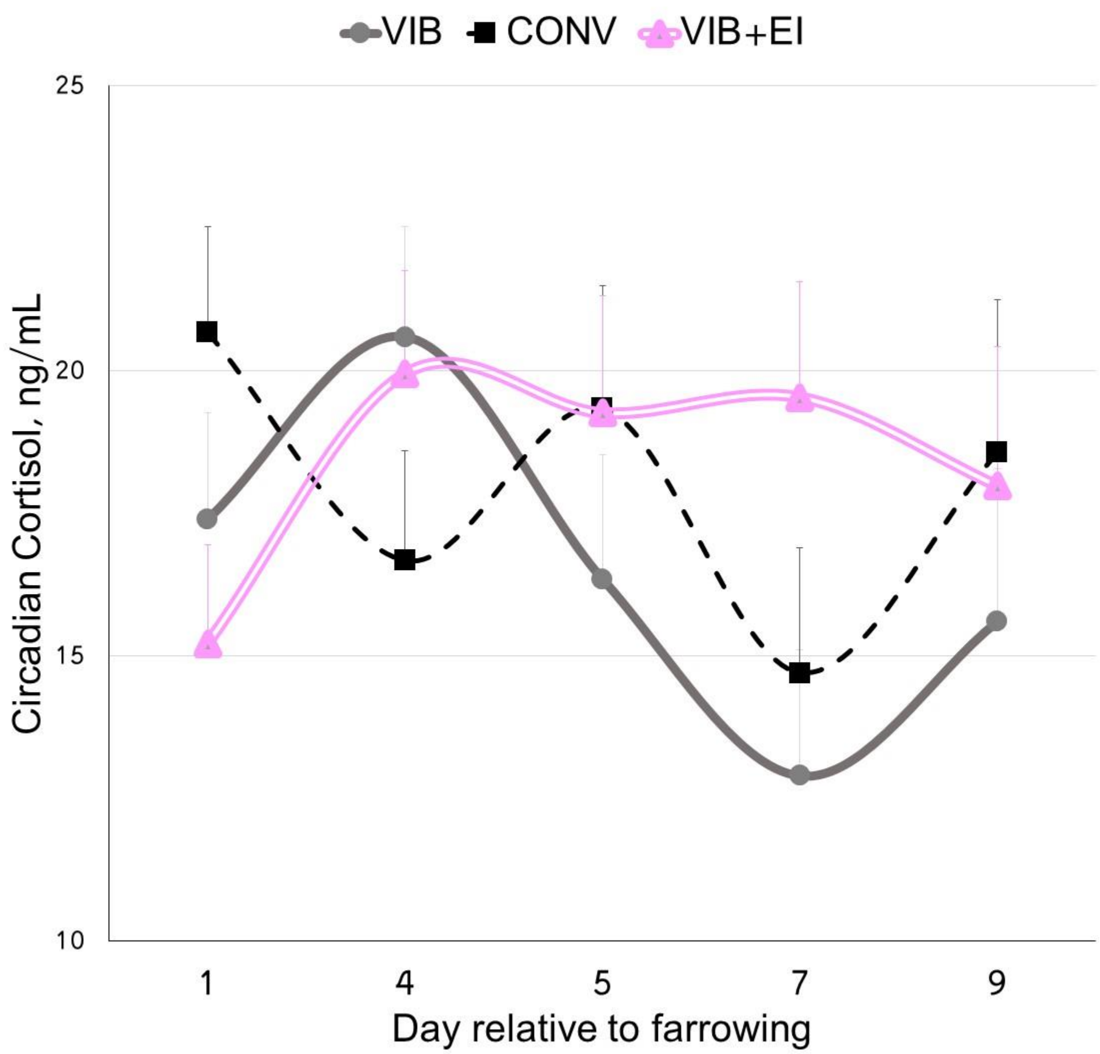
	Culled		5 days		4 days	
VIB	**4**		**3**		**9**	
	(4.31)	[-0.21]	(4.31)	[-0.89]	(7.38)	[0.97]
CONV	**7**		**7**		**4**	
	(4.85)	[1.42]	(4.85)	[1.42]	(8.31)	[-2.51]
VIB+EI	**3**		**4**		**11**	
	(4.85)	[-1.21]	(4.85)	[-0.56]	(8.31)	[1.57]

$\chi2(4) = 6.6440$, N = 52, $P = 0.1559$.

Supplementary Figure 2.1. Session Return-to-Resting Heartrate. After play-back of a piglet distress call, sows were treated with vibration-only (VIB, n = 16), conventional (CONV, n = 18; 3 hand slaps), and, vibration + electrical Impulse (VIB+EI, n = 18). This was conducted over 6 sessions. The time for sows to return to resting within the hour after each session was calculated. #LS-means tend (*P* = 0.07) to differ.



Supplementary Figure 2.2. Circadian Cortisol. After play-back of a piglet distress call, sows were treated with vibration-only (VIB, n = 16), conventional (CONV, n = 18; 3 hand slaps), and, vibration + electrical Impulse (VIB+EI, n = 18). The treatments were applied over 6 sessions on days 1 through 4 relative to farrowing. The mean of am and pm cortisol concentrations were evaluated for circadian cortisol on days 1, 4, 5, 7, and 9. Treatment x Time *P*-value = 0.04. Tukey's LS-mean comparison indicated that within day, no treatments were different (*P* > 0.10).



Chapter 3 - Aversive stimuli from crushing mitigation strategies affect nursing behaviors in pigs born (first or last)

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FOR CONSIDERATION OR SUBMISSION TO '*ANIMALS*'

SIMPLE SUMMARY

Piglet mortality is a glaring concern for swine producers. In immediate days after birth, piglet death is mostly due to crushing by the sow. Automated mitigation strategies that cause the sow to stand or jump if the piglet is being crushed may reduce mortality rates in the first three days after farrowing, however, the aversive stimuli used to cause the sow to jump up may alter her nursing behaviors. The alterations may disrupt an established order of suckling. Some piglets may be more affected by the change than other piglets in a litter. We previously investigated three stimuli (vibration, (VIB), control; hand-slap, (CONV), conventional, or; vibration followed by electrical impulse (VIB+EI), SmartGaurd technology) to cause sows to stand. This technology and its implications stretch to the suckling behaviors and overall welfare of the piglets as well. Swine managers will need crushing mitigation strategies in the future that are not only safe for the sow, but have no negative impact on the piglets as well.

ABSTRACT

Advancing technology to mitigate preweaning mortality rarely approaches the behavioral effect on the piglets. Piglet birth order and management status (transferred or not) as well as sow treatment in lactation impact future performance and welfare. Fifty-six sows and their pigs were exposed to novel technology to mitigate crushing in the first week of life. Three treatments were applied to the flank of the sow by remote as a distress call was broadcast; vibration (VIB, a device simply vibrated while making contact with the sow), conventional (CONV, a researcher used an open hand to slap the sow), vibration+electrical impulse (VIB+EI, the same device vibrates, and then delivers an electrical impulse). Aversive sow treatment disrupted nursing stability. More piglets in VIB+EI treatment missed nursing bouts over the course of treatment (P=0.001). Birth order was grouped into categories (piglets born 1-5, 6-11, 12-18, 19-21) and transferred piglets. Earlier born piglets had a shorter latency to suckle ($P = 0.05$). Piglets that were transferred were more likely to move anterior along the underline ($P = 0.09$). Transfer piglets and piglets in birth category three were less consistently in the same teat quadrant ($P = 0.05$). Piglet weight was taken at birth, day seven and weaning. Transfer piglets were largest throughout the study, and latest born piglets gained a higher percentage of body weight over the course of lactation ($P < 0.05$). The management combinations of automated technology to reduce mortality and cross fostering techniques both impact not only suckling behavior but production performance as well.

Keywords: Piglet, Lactation, Teat Order, Transfer, Welfare

INTRODUCTION

The lactation phase constitutes a bottleneck in swine production; the top 25 % of US commercial herds operate at an average of 29.1 ± 3.1 pigs/sow/year (Stalder, 2017). Exacerbating the issues of production and welfare is the fact that mortality rates are climbing. Currently, preweaning mortality ranges from 8 to 25 % (Stalder, 2017; Allonso-Spillsbury et al., 2007). The issues of piglet mortality and morbidity are intricate and combine behavioral and nutritional aspects.

Recent technological advancements are commercially available to mitigate mortality from crushing up to 30% compared to traditional efforts such as a farrowing crate (Swinetechnologies, 2021). The automated technology uses aversive stimuli to incite a sow standing response if the system detects a piglet giving a distress call. This technology is currently utilized on approximately 30,000 commercial sows, with a 90% success rate of sow response (Rooda, 2021). However, mitigation strategies without advanced technology, use aversive stimuli such as hand-slaps until the sow stands (Hutson et al., 1992). Previous work in our laboratory indicated that sows treated with the aversive stimuli (hand-slap or vibration followed by electrical impulse) reduce the amount of time resting in the lateral position and increased latency to start a nursing bout compared to sows treated with an innocuous stimulus (vibration-only) (Mumm et al., 2020). Further investigation into individual piglet behaviors during the time sows were treated to decrease crushing mortality was required. The behaviors that sows perform (i.e. the 5 nursing phases) are required to optimize nutrient uptake by piglets (Pedersen et al., 2011). Disruption of this can have negative impact on nutrient availability for piglets. Nutrient deficiency leads to an increase in mortality (Ison et al., 2017; Hasan et al., 2019).

There may be a multitude of factors that influence the individual choices of piglet behaviors. Multiple researchers echo the importance of suckling anterior teats on growth performance (Fraser and Jones, 1975; de Passille and Rushen, 1989; Skok et al., 2007). However, more recent data indicates that there is not a correlation between anterior teats and piglet performance (Lichtenwalter, 2018). Balzani et al., (2016) found that piglets suckled more from both posterior and anterior teats immediately after birth, avoiding the middle sections of teats, with early born piglets selecting posterior teats as well. Devillers et al. (2007), studied 40 commercial sows and found that piglet vitality, birth weight and litter weight variation were directly related to colostrum intake. To add complexity to the production systems and the influence of the aversive stimuli on the sow, then her piglets, is cross fostering. Cross fostering is utilized in 98 % of commercial farms in the US and Canada (Straw et al., 1998). Pajzlar and Skok (2019), found that an age advantage of 1 to 1.5 days induced more active suckling when piglets were introduced to a foster litter. Also, piglets fostered into litters that were of equal or greater size were more successful in suckling after transfer (Pajzlar and Skok, 2019).

The day which stable teat order is acknowledged after parturition is variable between day 1 and day 13 (de Passille et al., 1988; Litten et al., 2003; Arnold et al., 2019). Popular averages for teat order development are more commonly between day 4 (Puppe and Tuchscherer, 1999) and day 10 (Skok and Škorjanc, 2014). The establishment of a teat order can be attributed to increased survival when compared to litters or piglets where there is no continuity or stability amongst teats (Skok and Škorjanc, 2014). The behavioral and social aspects of pork production in early life, impact later life social interactions (Litten et al., 2003; Canario et al., 2017; Peden et al., 2018; Weller et al., 2019). In recent years the behavioral impact of less competition during lactation, has seen changes in activity level and latency to consume feed in the nursery phase (Sommavilla et al., 2015; Middlekoop et al., 2019).

We hypothesized that early born piglets had more available teats to select, and time to establish teat dominance, therefore their suckling behaviors would be more prone to destabilization by the aversive stimuli for crushing mitigation.

MATERIALS AND METHODS

Animals and Housing

The experiment was conducted in Oct-Nov 2017 at Kansas State University Swine Teaching and Research Center (Manhattan, KS). Animals were housed and managed in accordance to the 'Guide for the Care and Use of Agriculture Animals in Research and Teaching' (FASS, 2010). All procedures were approved by the Kansas State University Institutional Animal Care and Use Committee (IACUC; Protocol #3913).

Multiparous sows (DNA line 241; Table 2) produced total of 759 piglets (Table 2). Traditional farrowing stalls were 2.3 m long, 0.43 m wide and 1.5 m height and no substrate was provided. At the front of the stalls, sows had a feeder (GESTAL, Jyga Technologies, St. Lambert De Lauzon, Qc, Canada) and to the right a drinker. Piglets could access the drinker easily and some could climb into the feeder, no piglet creep feed was provided. The farrowing stalls included heat sources via lamps, at the rear right side of the stall. Piglets were processed (ear notch, tail docking, castration) at age 1 d, on a per farrowing day basis (d 0= farrowing ± 0.74 d SD block 1; ± 0.93 d SD block 2). Prior to farrowing house entry, one camera (Points North Surveillance Inc., Auburn, ME, USA) was fixed to the ceiling above every two crates for continuous video recording throughout farrowing and lactation. One researcher reviewed all farrowing and nursing data throughout lactation (Figure 3).

Piglet Identification and Nursing Data Collection

Researchers were present for all farrowing's and piglet birth order was identified by a sagittal strip of tape on the dorsal side of the animals (Figure 1). Color variation consisted of 21 unique colors or patterns for piglets ranging from red – blue and including patterns (Figure 1). Piglets were re-marked as necessary. The initial teat quadrant that piglets selected immediately after birth was documented by one observer (Figure 3). Nursing behavior was documented in three nursing bouts throughout the day (0 = 2401 to 0800, 8 = 0801 to 1600, 16 = 1601 to 2400) on days 1, 2, 3, 4, 5, 6, 7, 11, 17, and 20 (pre-weaning), relative to farrowing (Figure 3). Teat location was divided into four quadrants along the sows' underline (Figure 2). Each quadrant contained four teats, except for sows with fewer than 16 teats, where quadrant 4 would have 2 teats. No differentiation of top or bottom row suckling was noted. Thus, quadrant 1 remained the same regardless of sow direction, likewise for the other three quadrants. Litters were balanced based on farm SOP's, in which piglets were transferred based on matching size in the new litter with available teat space. All transfers took place within 48 hours of birth. Transferred piglets were identified by litter of origin yet measured with the litter in which they were reared. Piglet total plasma protein (Reichert-Jung 0 50° Brix hand-held refractometer) was used as a nursing-quality measure. At birth, each pig was weighed, and 500 uL of umbilicus blood was stripped into a heparinized tube. It is important to note that the blood was collected pre suckling. All pigs were weighed on day 7 relative to farrowing and 500 uL of whole blood was collected from every other gilt via jugular-venipuncture. Plasma at birth and day 7 was harvested after centrifugation and stored at -20°C until refractometer analysis. Additional weights were collected for the experiment at birth, age 7 d and age 21 ± 0.84 d SD. A timeline of measures and procedures can be seen in Figure 3.

Sow Treatment

One day 1 ± 0.84 after farrowing, a device (SmartGuard, SwineTech Inc) was affixed to the flank region of each sow with adhesive patches. Sows were treated with one of three treatments to incite a standing response while a piglet distress squeal was broadcast. 1) Vibration (VIB), the device was triggered and a vibration and served as an innocuous control stimulus; 2) Vibration + electrical impulse (VIB+EI), the vibration was administered followed by electrical impulse and, 3) Conventional (CONV), consisted of three open hand slaps to the back (2) and side (1) of the sow by the same handler. Sow treatment took place over four days in six sessions in the afternoon and evenings (Figure 3). For complete sow treatment and reaction see Mumm et al. (2020).

STATISTICAL ANALYSIS

Piglet birth order was recategorized into 1 thru 4, (1 = piglets born 1 -6; 2 = piglets born 7 – 12; 3 = piglets born 13 – 18; 4 = piglets born 19 – 26). A fifth category (5) was included for piglets that were transferred to other sows for lactation. Time was accounted for as piglets age relative to the day treatment began. Mixed model analysis was performed using Proc Glimmix, (SAS 9.4; SAS Institute, Cary, NC). Fixed effects were: Birth order category, sow treatment and time. The interaction of treatment by birth order and treatment by time were included. Farrowing block (October or November) was included as a co variate and sow number was used as a random variable. *P*-values shown represent the Type III test of fixed effects.

RESULTS

The average number of piglets born alive to sows in the present study was 14.97 ± 2.70 SD, ranging from 5 to 21 (Table 2). Average birthweight of piglets was 1.30 ± .33 kg SD with the minimum and maximum birthweight throughout the study being 0.45 and 2.45 kg, respectively (Table 2). Birth order had no influence on the sex of the piglets ($\chi 2$ (719, N= 721) = 4.48, P = 0.11 data not shown). For this project, mortality rate was 7.4% overall. The deaths were broken down into birth categories, potential causes, and sow treatments (Table 3). Fostered piglets fed by VIB-treated sows were at the greatest risk of mortality, but the causes of death were unknown to the veterinary and management staff (X^2 8, n = 55, 84.18, $P < 0.001$). Fourth-birth category pigs had the second greatest mortality rate. All of the deaths related to crushing occurred among piglets nursed by VIB-EI treated sows (X^2 8, n = 55, 84.18, $P < 0.001$). During the treatments, VIB+EI-sows crushed 2 first- borns, 2 second-borns and 1 fourth-born; crushing did not occur among the other sows. However, similar rates of crushing among these treatment and birth order categories were observed before the stimuli were applied.

After birth piglets born in the first category selected posterior teats to suckle more often than anterior, whereas later born piglets in categories 2, 3 and 4 selected from anterior teat quadrants more than expected (X^2 3, n = 730, 34.14, $P < 0.001$; Table 4). The latency for piglets to obtain colostrum via suckling after birth increased with birth order $P = 0.058$, adjusted R^2 = 0.006 (Supplementary figure 1).

Birth order and treatment impact on suckling success

There were no notable birth order category influences or birth order category*time interactions for the change in percent of pigs that missed a meal ($P > 0.10$). However, there was a treatment*time interaction for the days which sows were exposed to treatment and the first few days after the treatment sessions ended (Figure 4 and Figure 5; $P \leq 0.05$). On the first observation the day treatment began, piglets suckling sows treated with VIB+EI stimulus were less likely than other treatments to miss a meal (Figure 4; $P < 0.05$). Although, on the final observation the day of treatment, it was the VIB treated pigs that were least likely to miss the suckling opportunity (Figure 4; $P < 0.10$). On day two relative to treatment the piglets on sows treated with VIB were more likely to miss suckling compared to CONV and VIB-EI for the first observation ($P < 0.05$), but the second observation saw more VIB+EI piglets missing the nursing bout than the other treatments (Figure 4; $P < 0.05$). On the 6th day of the experiment, the percent of VIB-EI pigs to miss a meal changed the least, while pigs treated with aversive stimuli (CONV and VIB+EI) had increased the percent of pigs that missed a meal (Figure 5). In addition, the midnight after pigs were all handled and blood collected (day 8), VIB+EI pigs had an increase in pigs that missed a meal whereas there were no differences between CONV and VIB pigs (Figure 5; $P \leq 0.05$). There were no significant influences of birth order category, treatment, birth order catagory*time, treatment*time or birth order category*time for the change in pigs that missed a meal when sample days 10-18 were analyzed ($P \geq 0.10$).

Piglet movement along the underline

The interaction of treatment and time impacted the magnitude of change along the underline for piglets (Figure 6; $P < 0.05$). Variation exists while treatments are taking place, in the final observation of day one, and the first two observations of day two. Vibration treated (VIB) piglets are more likely to be promoted (move anterior) than VIB+EI piglets on day one (Figure 6; $P < 0.05$), whereas VIB+EI piglets were more likely to be promoted compared to the VIB and CONV piglets for first observation of day two (Figure 6; $P < 0.05$: Figure 8; $P < 0.05$). Conversely on the second observation of day 2 the VIB+EI treated piglets are least likely to be promoted compared to the other two treatments (Figure 6; $P < 0.05$: Figure 8; $P < 0.05$). The first observation on day eight relative to treatment VIB+EI piglets are more likely than the other two treatments to be demoted along the underline (Figure 6; $P < 0.05$), and least likely to select the same udder quadrant as previously used compared to VIB or CONV treatments (Figure 9; $P < 0.10$). The last observation day, CONV piglets are demoted more than VIB piglets, but not VIB+EI during the first observation (Figure 6; $P < 0.05$). However, the second observation the VIB+EI piglets are demoted more than both VIB and CONV piglets (Figure 6; $P < 0.05$). For the final observation the VIB piglets are demoted more than both the VIB+EI and CONV piglets (Figure 6; $P < 0.05$). There were not significant or tendency differences among birth order for demoted measures ($P > 0.10$).

In terms of birth order category piglets that were fostered, or category 5, tend to be promoted more than all other categories (Figure 7; $P = 0.093$). Similarly, the piglets that spent more suckling bouts in the same or consistent udder quadrant were piglets born in the third category or those that were fostered (Figure 7; $P = 0.055$). Teat selection became stable with piglets on VIB+EI treated sows establishing teat preference on day 3.8 vs days 4.8 and 4.4 for VIB and CONV piglets respectively ($F = 7.62$; $P = 0.0005$).

DISCUSSION

Piglet suckling dynamics are an important aspect of health and welfare especially when suckling sows subjected to novel technologies. The current study analyzed the impact of a novel sow treatment to decrease piglet mortality via crushing on the suckling dynamics and behavior or piglets. Traditionally birth order has impacted piglet body weight, thus future health and performance (Tuchscherer et al., 2000; Smith et al, 2007; Fix et al., 2010). Latency to ingest colostrum is implicated throughout literature as having negative impacts on piglet morbidity and mortality (Fraser and Jones, 1975; Baxter et al., 2008; Pedersen et al., 2011; Ison et al., 2017; Hasan et al., 2019). The present study saw earlier born piglets have a shorter latency to suckle. Each additional piglet that is born increases the latency to suckle by 72.2 seconds. Although differences in the latency for piglets to suckle and similar timeframes were seen in (Balzani et al., 2016). Meaning minimal advantages if any in colostrum intake.

The causes of death indicate that the influence of birth order was more likely the influence of mortality among 4th order pigs than treatments for this project. Fourth order pigs may be at higher risk for malnutrition in utero and hypoxia during parturition (Wu et al., 2006; Baxter and Edwards, 2018). Fourth order pigs are only born to sows that have 19 or more pigs in a litter, which implies they are born when the number of teats are already taken. This can potentially make them miss meals or make them more motivated by competition to stay near the sow, even when she is moving from a stand position to a lie position. Nonetheless, mortality events in this project will remain more of a speculative notion than evidence because more 4th order pigs and foster pigs need to be evaluated in large scale production systems with overly prolific sows. To avoid the conundrum of supernumerary piglets cross fostering piglets is a common production tactic to regulate both litter number and litter size. It is noteworthy in the present study that foster piglets per the SOP of the farm used were more often than not, the larger piglets in the litter. This causes confounding results that must be taken with caution moving forward as the reader considers implications of fostered piglets. For the present study fostered piglets as well as piglets born in category four showed higher percentage of body weight gain over the course of lactation.

Establishing a teat hierarchy is important, as anterior teats produce more, and higher quality milk (Spinka and Illmann, 2015; Clemmons, 2020). This was not the case for Puppe and Tuchscherer, (1999) where piglets suckling posterior teats tended to have lower weight gains. Despite the lack of empirical advantages in teat position found in this study, there is still competition and movement along the underline in the days immediately after birth where piglets from every treatment make noticeable attempts to move more anterior along the underline. In the present study, early born piglets first suckled at more posterior teats in quadrant 4, and later born piglets first suckled more anterior teats. This progression would indicate that the later born piglets are simply suckling at the available teats. Balzani et al., (2016) found that piglets suckled more from both posterior and anterior teats immediately after birth, avoiding the middle sections of teats, with early born piglets selecting posterior teats as well. The fact that anterior teats are close to the sows midline, making them more easily accessible is also discussed (Balzani et al, 2016). The present study did not investigate any morphological aspects of the underline, besides dividing it into quadrants, and noting that the fourth quadrant in sows with fewer teats may only have one teat pair. It is suggested by de Passille et al., (1988) that there are advantages to establishing high teat fidelity (stability) early in lactation such as fewer missed nursing's and an increase in weight gain within the first three days of lactation. In the current study, stability among teat quadrants during suckling bouts, occurred around day 4. These values range however from 2 hours post-partum (Arnold, 2019), to two weeks (de Passille et al., 1988).

There was no creep feed available for the piglets in the present study. Thus, their nutrition was directly related to suckling from the sow, thus being present for a suckling bout that is uninterrupted and complete is paramount. Piglet early life nutrient availability is the first limiting factor to their growth. Further disruptions to sow suckling behavior can also impact this piglet growth. Sows will nurse at intervals of 36 to 50 min (Quesnel et al., 2015), allowing for more than 24 nursing bouts/day. So, it is unlikely that a singular observation or a small number of missed nursing bouts will have any effect on piglets. This is also corroborated with the performance data that was collected at weaning. However, the phases of a nursing bout are both behavioral and physiological, thus, any stressful alteration in the sow behavior or physiological stimulus to the sow could prevent the nursing from being successful (Pedersen et al., 2011).

These could be as simple as the sows aversion to workers or any prolonged stress from the treatment early in lactation. Mumm et al. (2020), found that sows treated with aversive stimuli from farm workers had higher stress levels for longer periods of time. Piglets suckling sows that were treated with harsh stimuli did not move anterior along the underline as much as piglets treated with the mild, or control stimuli. Though, piglets in the electrical impulse group were also demoted less than their counterparts in the other treatments. The impact of sow treatment on the movement along the underline was largely during the time of sow treatment, and at the very end of lactation. The piglets were weighed and had blood collected on day 7 of lactation. The ensuing nursing bouts showed more variation in promotions and demotions, after the significance level for teat quadrant stability had been reached. This would indicate that, although suckling patterns seem to be consistent and robust in piglets that attempt to move anterior along the underline, and establish stable teat order, any disruption to either sow or piglets has an impact on this consistency.

CONCLUSIONS

Obstacles of piglet mortality, based on crushing as well as lack of nutrients, still hinder swine production. Especially as production goals are based on increasing number of piglets born, and their growth (Stalder, 2017). More effort needs to be applied to modern commercial piglets' behavior and suckling strategies immediately after birth, especially as novel technologies to increase piglet numbers or changes to sow production are being rapidly developed. In the present study disruptions to natural suckling patterns of the sow through use of this technology impacts the consistency of teat selection by piglets. Which can have a potential impact on performance and development. Consistencies with literature in the teats that are first suckled postpartum are found in the present study. Early born piglets suckle the posterior teats more frequently to obtain colostrum, leaving later born piglets to suckle more anterior teats immediately after birth. Stable teat quadrants are achieved around day four. These authors suggest more effort be put into the behavioral aspect of neonatal piglets, especially those that are transferred on large scale production farms. The current study provides valuable observations regarding birth order and the impact of novel sow treatment on the neonatal performance and welfare of piglets.

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Table 3.1. Description of measurements.

Measure	Definition	Units
Birth ± 24 h		
Latency from birth to suckle	Interval between birth until first time latched on the udder.	Seconds
Quadrant first suckled	Sow underline split into quadrants (Figure 2) 1, 2, 3, 4.	Numeric
Plasma Protein Birth	Umbilical blood was striped pre suckling and plasma was measured using a refractometer.	Brix
24 h Thru Lactation		
New Quadrant chosen	Observation day where piglet changes teats from that which was first suckled.	Day
Stabilization reached	Day where piglet first suckles the teat at which it remains for three consecutive days.	Day
Udder location same	Number of observation days where piglet suckles the same quadrant as first meal.	% of total observations
Udder location change	Number of observation days where piglet changes teat quadrants from first meal.	% of total observations
Demotions	Percent observations that the piglet's choice was 1 or more quadrants less than its previous meal choice.	% of total observations
Promotions	Percent observations that the piglet's choice was 1 or more quadrants more than its previous meal choice.	% of total observations
Displacement	Percent observations that the piglet was displaced up or down from the teat quadrant of their first meal.	% of total observations

Table 3.2. Scope of Inference and Piglet Body Weight. [1]Three treatments were applied to sows using SmartGuard™ technology (Swinetech Inc., Iowa, USA) where a device was affixed to the sows flank region and triggered by a researcher while a piglet distress call was played in an effort to make the sow stand. VIB (vibration), the device simply vibrated similar to handheld mobile devices, CONV (conventional) the sow was slapped with an open hand (2 side, 1 back) by the same researcher, VIB+EI (vibration + electrical impulse) the device first vibrated then an electrical impulse was applied after a slight delay.

[2]Piglets were allocated to birth order categories: 1 (piglets 1-6), 2 (piglets 7-12), 3 (piglets 13-18), 4 (piglets 19-26).
[a,b,c] Indicate differences at $P \leq 0.05$ within rows

	Treatment[1]				Birth order category[2]						*P*-values		
	VIB	CONV	VIB+EI	SEM	1	2	3	4	5	SEM	TRT	BOCat	TRT*BOCat
n =													
Litters	16	17	19		52	49	47	13	15		--	--	--
Pigs	248	226	271		286	262	140	17	40				
Body weight, g													
age 0	132	133	132	± 6.0	130	128	132	142	--	± 9.0	0.980	0.280	--
day 7	266	260	279	± 10.0	254	255	265	288	280	± 12.0	0.160	0.080	0.300
at weaning	557	557	593	± 21.0	541[a]	545[a]	565[b]	581[b,c]	613[c]	± 36.0	0.090	0.040	0.410
Percent Δ of bodyweight													
during	109	95	102	± 3.8	99	99	97	103	89	± 10.3	0.21	0.71	0.17
after	109	105	114	± 5.3	115	114	114	101	103	± 8.8	0.29	0.31	0.59
overall	312	310	318	± 15	328	326	322	288	303	± 26.2	0.85	0.43	0.78

Table 3.3. Piglet Mortality for Study Duration.

	Before[1]					During[2]				After[3]			
	Alive[4]	Still[5]	Crush[6]	Mal[7]	Other[8]	Alive[4]	Crush[6]	Mal[7]	Other[9]	Alive[4]	Crush[6]	Mal[7]	Other[10]
VIB	248	40	0	1	1	238	0	2	8	230	0	1	7
1st (1-6)	93	3	0	0	0	90	0	1	2	88	0	0	2
2nd (7-12)	82	12	0	1	1	80	0	1	1	77	0	0	3
3rd (13-18)	54	21	0	0	0	53	0	0	1	50	0	1	2
4th (19-24)	10	4	0	0	0	10	0	0	0	10	0	0	0
Fostered[11]	9	0	0	0	0	5	0	0	4	5	0	0	0
CONV	226	18	0	2	1	232	0	2	2	223	0	2	7
1st (1-6)	95	3	0	0	0	94	0	0	1	88	0	2	4
2nd (7-12)	79	4	0	1	1	76	0	2	1	74	0	0	2
3rd (13-18)	29	9	0	1	0	29	0	0	0	28	0	0	1
4th (19-24)	1	2	0	0	0	1	0	0	0	1	0	0	0
Fostered[11]	22	0	0	0	0	32	0	0	0	32	0	0	0
VIB+EI	271	28	4	1	3	237	5	3	26	227	0	0	10
1st (1-6)	98	5	2	0	0	88	2	1	7	86	0	0	2
2nd (7-12)	101	6	1	1	1	87	2	1	11	83	0	0	4
3rd (13-18)	57	12	0	0	2	48	0	1	8	46	0	0	2
4th (19-24)	6	5	1	0	0	5	1	0	0	4	0	0	1
Fostered[11]	9	0	0	0	0	9	0	0	0	8	0	0	1

[1]In days relative to the first treatment, no. piglets from: Birth to 0 (Stdev = 5.9); [2]days 0 to 3, and; [3]days 4 to 21 (weaning).

[4]No. of possible live piglet observations in the litter at the time of sample, whether they were identifiable or not.

[5]Stillborns were piglets that were not breathing, or dead before first feeding could take place.

[6]If bruising or injury could be detected, they were counted as crushed, including injury followed by euthanization.

[7]If video data confirmed that there was 2 or more no sucks in the 6 previous samples, the death was determined as malnutrition/dehydration.

[8,9,10]Death from unknown causes.

[11]Pigs were fostered by the swine manager 24 hours after birth to 4 hours before the first treatment (0) at 1600 h. Two Sows died during parturition, and surviving piglets were fostered

Table 3.4. Chi-Square analysis of birth quadrant first suckled by birth order.

		Teat quadrant first suckled[1]											
		1			**2**			**3**			**4**		
		Actual	*Expected*	*chi-square*	Actual	*Expected*	*chi-square*	Actual	*Expected*	*chi-square*	Actual	*Expected*	*chi-square*
Birth Order[2]	**1**	40	*60.62*	*7.01*	42	*54.15*	*1.4*	88	*77.59*	*1.4*	125	*102.64*	*4.87*
	2	67	*55.89*	*2.21*	55	*49.93*	*1.86*	60	*71.54*	*1.86*	90	*94.64*	*0.23*
	3	38	*31.23*	*1.47*	36	*27.9*	*0.03*	41	*39.98*	*0.03*	37	*52.89*	*4.77*
	4	5	*2.26*	*3.32*	1	*2.02*	*0*	3	*2.89*	*0*	2	*3.83*	*0.87*

Chi Square 3, n = 730 = 34.14, $P < 0.001$.

[1] The sows udder was divided into quadrants (anterior to posterior) with teat quadrant number 1 representing the two top and two bottom teats closest to the sows head, and teat quadrant four representing the 4 most anterior teats (top and bottom).

[2] Birth order was divided into 4 categories; 1 (piglets 1-6), 2 (piglets 7 - 12), 3 (piglets 13 - 18), 4 (piglets 19 - 26)

Figure 3.1. Piglet order identification scheme. **Left)** Birth order was denoted by color coded duct tape that was affixed in a sagital stripe on the back of each piglet. For litters greater than 17 pigs, white tape was used as well as traditional silver duct tape. A cross pattern with 2 strips of tape was also used when necessary. **Right)** Camera view of piglets suckling where identification is visible. Arrows indicate piglets 5, 16, 10 and 12. The observer may be required to move forward or back in the video to identify each piglet.

Order ID	Tape ID
1	NeonPink
2	LightPink
3	Magenta
4	Red
5	Yellow
6	NeonGreen
7	DarkGreen
8	LightGreen
9	LightBlue
10	Cyan
11	Cobalt
12	Purple
13	Black
14	Checker
15	Mojave
16	Zebra
17	mustache
18	silver
19	white
20	medial stripe
21	cross pattern

Figure 3.2. Quadrant breakdown of sow underline. Sow and piglet view where each teat quadrant is visible. Q1 represents teat quadrant number one. Q2 represents teat quadrant number two. Q3 represents teat quadrant number three. Q4 represents teat quadrant number four. The anterior teats are positioned towards the head of the sow, and posterior teats are positioned towards her rear. Teat quadrants remain the same regardless of sow direction. Piglets not actively suckling at a quadrant during observation were classified as no meal.

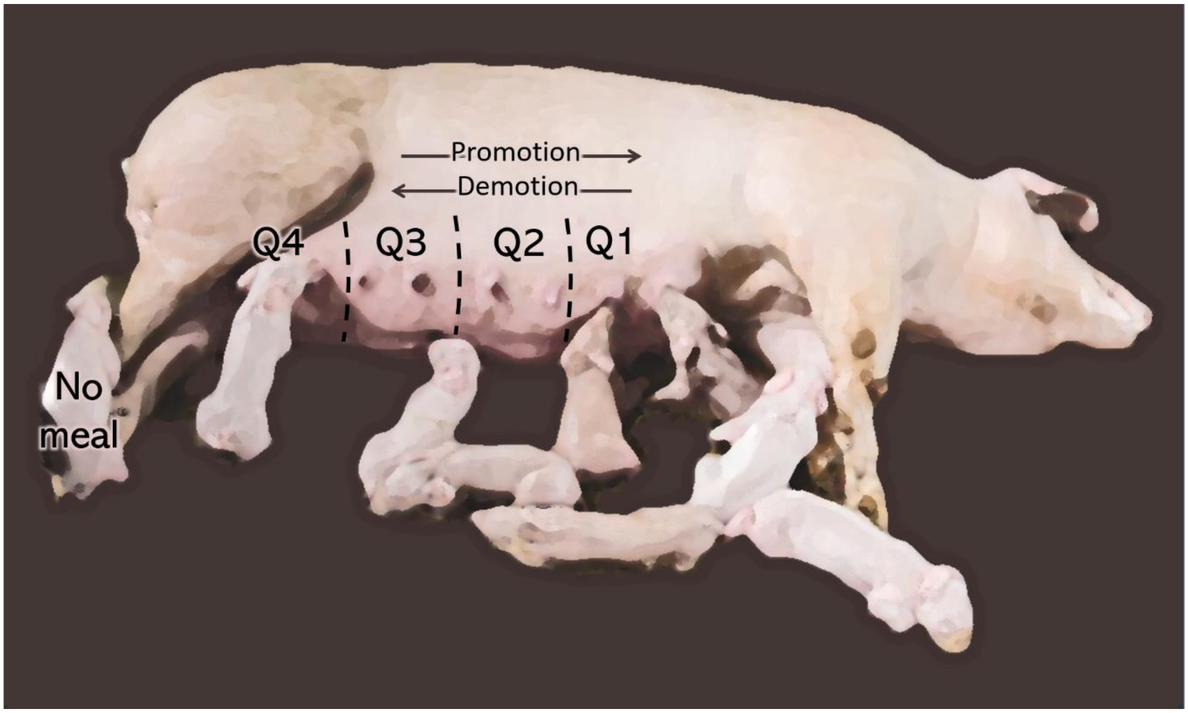


Figure 3.3. Timeline of sow treatment and piglet suckling observations during lactation. At birth piglets were weighed, umbilicus stripped for blood plasma protein, and birth order identified per Figure 1. Sows and piglets were recorded for the duration of lactation. The teat quadrant which was first suckled to obtain colostrum was documented by one observer. Cross fostering was done per farm SOP's to match piglet size and teat availability. All cross fostering was completed by day 2 relative to farrowing. Sow treatments were applied after all sows had farrowed (d 0 ± 0.84). Sows wore a patch adhered to the flank region, which contained a supplied device (SmartGuard™, SwineTech Inc, Iowa, USA) to treat sows with one of three conditions aimed at inciting standing while a piglet distress call was broadcast. 1) Vibration (VIB, n = 16) the device simply vibrates synonymous with any handheld mobile device while making contact with the skin, 2) Vibration + Electrical Impulse (VIB+EI, n = 18), the device vibrates as previously described but is followed by a mild electrical impulse 3) Conventional (CONV, n = 18), a handler uses 3 open hand slaps to the sows side (2) and back (1). Day 1 of lactation relative to farrowing, one observer documented the teat quadrant that was suckled by each piglet for three separate nursing bouts (0 = h 2401 – 0800, 8 = h 0801 – 1600, 16 = 1601 – 2400). These observations were repeated on days 1 thru 7, day 11, 17 and 20 relative to farrowing. On day 7, piglet body weight was taken, as well as blood collection via jugular venipuncture for every other gilt in the litter to measure plasma protein. Piglet body weight was taken again at weaning for all piglets.

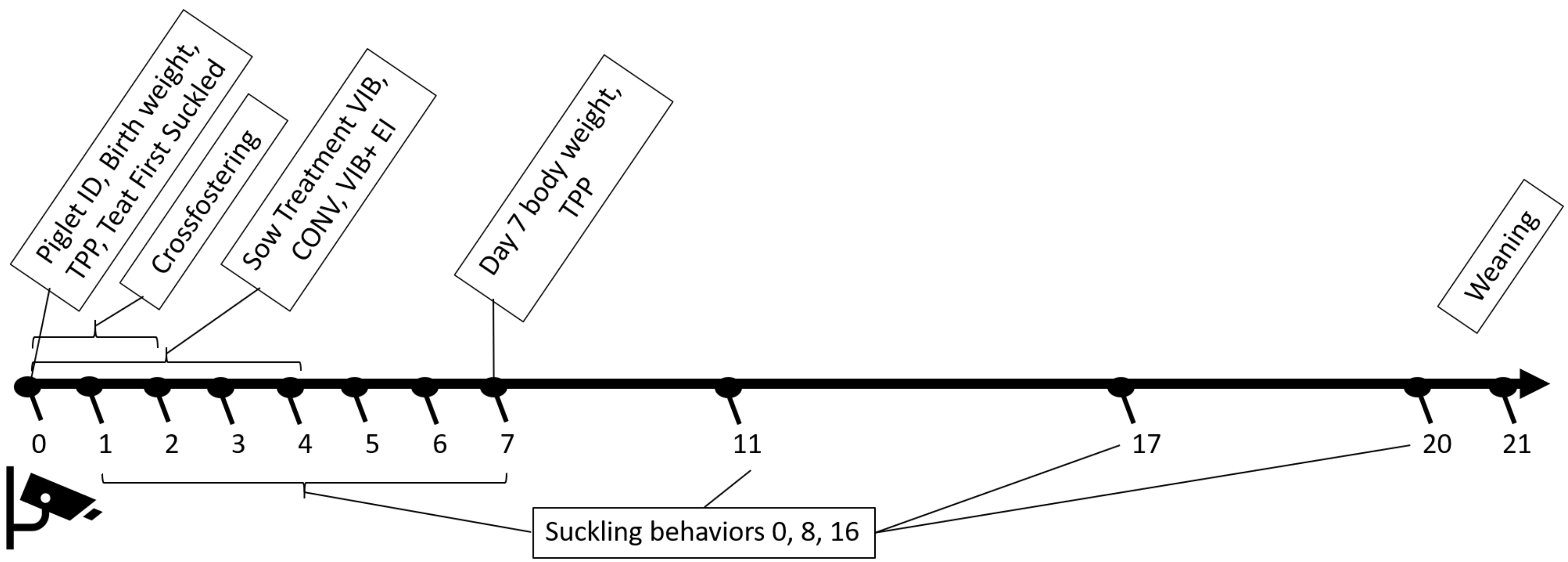


Figure 3.4. Percent of piglets that missed a suckling bout on days 0 thru 4. Percent piglets per litter that missed a suckling bout (change from the previous observation in percent) for treatment d 0 to 4 and video samples of nursing bout measures collected at 0000, 0800, and 1600 h. Treatments (VIB, vibration, n = 16 litters; CONV, hand slaps, n = 17; VIB+EI, vibration followed by electrical impulse, n = 19) were applied twice on day 0 at 1600 and 1800 h, and 4 at 1600 and 1800 h, and once on days 2 and 3 at 1500 h. Significant treatment by time interactions were seen on days 0 thru 4 relative to treatment $P = 0.001$. LS-means Sliced Time x Treatment Tukey-Kramer adjusted P-values $^{*}\leq 0.05$ and $^{\#}\leq 0.10$.

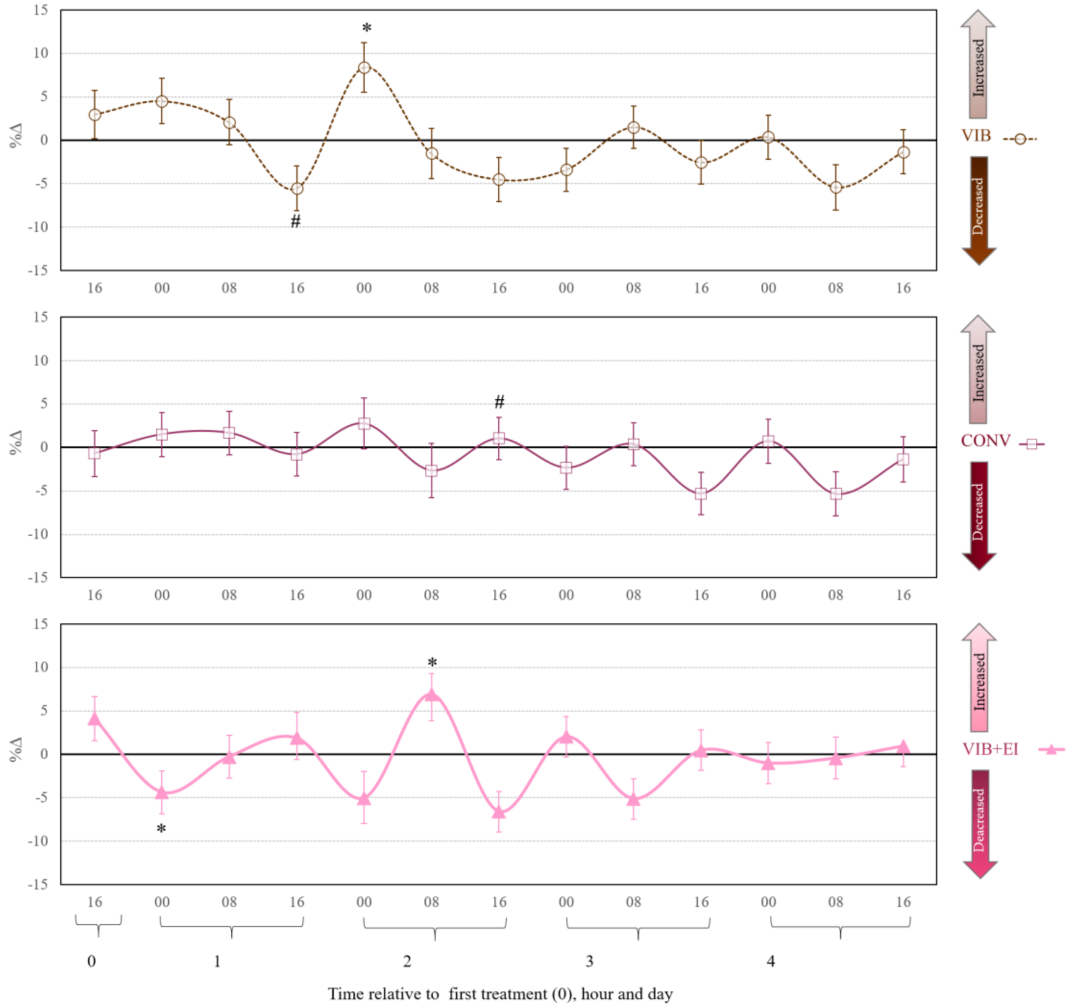


Figure 3.5. Percent of piglets that missed a suckling bout on days 5 thru 9. Percent piglets per litter that missed a suckling bout (change from the previous observation in percent) for treatment day 5, 6, 8 and 9 and video samples of nursing bout measures collected at 0000, 0800, and 1600 h. Treatments (VIB, vibration, n = 16 litters; CONV, hand slaps, n = 17; VIB+EI, vibration followed by electrical impulse, n = 19) were applied twice on day 0 at 1600 and 1800 h, and 4 at 1600 and 1800 h, and once on days 2 and 3 at 1500 h. A significant treatment by time interaction on days 5 thru 9 relative to the first treatment was found, $P = 0.053$. LS-means Sliced Time x Treatment Tukey-Kramer adjusted *P*-values *≤ 0.05.

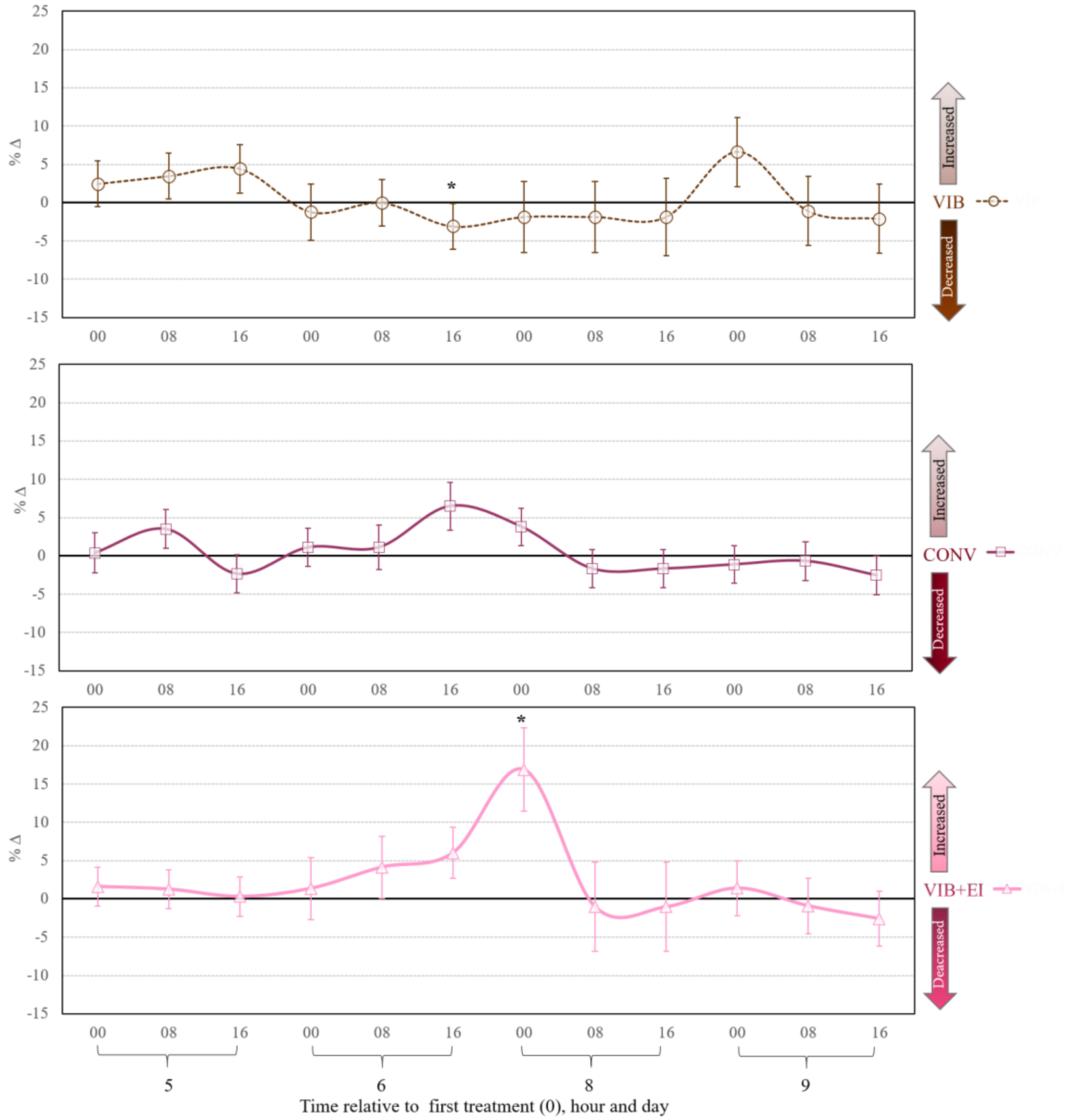
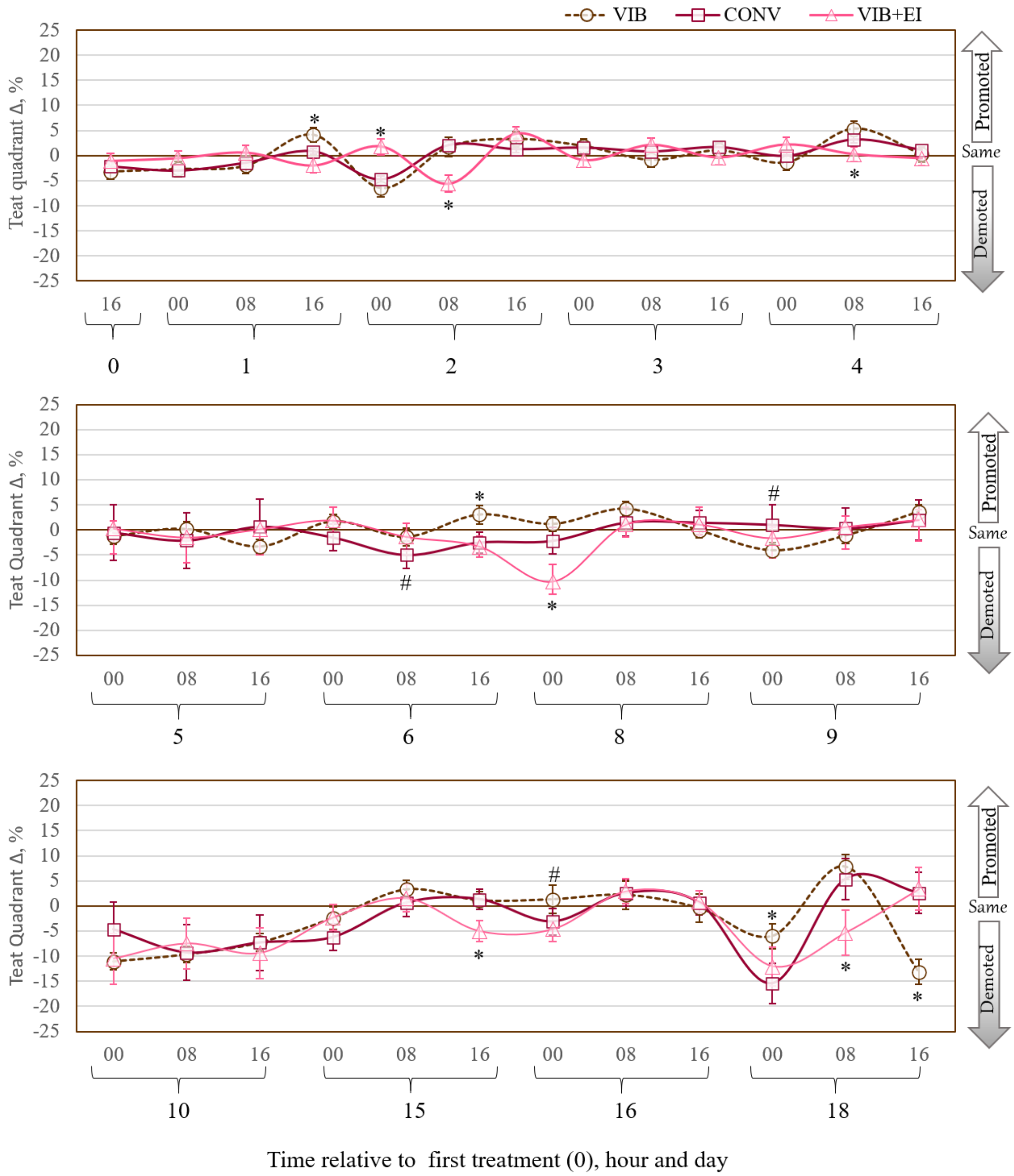


Figure 3.6. Average magnitude to change suckling quadrants per pig. Each sample result was compared to the previous, and movement up the udder line towards the head (No meal to Q4, Q4 to Q3, etc) was calculated as a 25% positive change, and down the udder line as a 25% negative change. If there was no change in quadrant status, then pigs were scored as 0. Treatments (VIB, vibration, n = 16 litters; CONV, hand slaps, n = 17; VIB+EI, vibration followed by electrical impulse, n = 19) were applied twice on day 0 at 1600 and 1800 h, and 4 at 1600 and 1800 h, and once on days 2 and 3 at 1700 h. Treatment by time interaction was significant for days 0 thru 4 P = 0.001. Treatment by time interaction was significant on days 5 thru 9 P = 0.003. Treatment by time interaction was significant on days 10 thru 18, P < 0.001. LS-means Sliced Time x Treatment Tukey-Kramer adjusted *P*-values $^{*}\leq 0.05$ and $^{\#}\leq 0.10$.


VIB
CONV
VIB+EI
Teat quadrant Δ, %
Teat Quadrant Δ, %
Promoted
Same
Demoted
25
20
15
10
5
0
-5
-10
-15
-20
-25
16
00
08
0
1
2
3
4
5
6
8
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16
18
*
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Time relative to first treatment (0), hour and day

Figure 3.7. Udder Quadrant selection by birth order category. Percent piglets per group per litter that chose the same quadrant as previously observed (including no teat selected) or were promoted (moved up one or more quadrants on the udder). Video samples of nursing bouts were analyzed by one observer three times per day (2401-0800, 0801-1600, 1601-2400). ##,# indicate difference at $P \leq 0.05$ and $P \leq 0.10$ respectively. Cross Fostered pigs tended ($P = 0.093$) to be promoted more than their contemporaries in other birth categories. Cross fostered and category 3 born piglets selected that same udder quadrant as their previous selection fewer percentage of times than birth categories 1, 2 and 4 ($P = 0.55$).

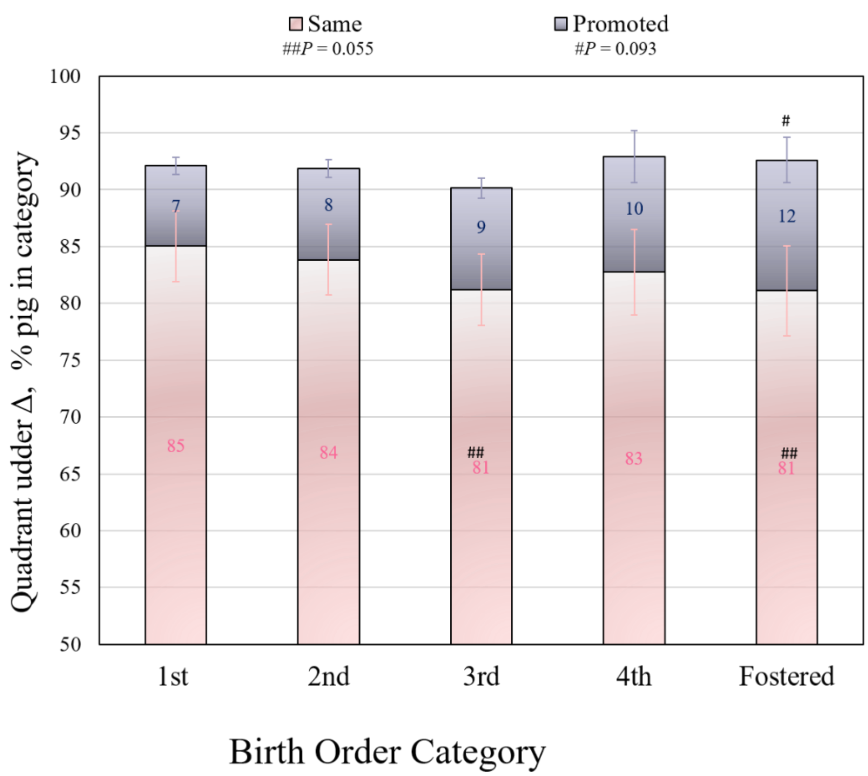


Figure 3.8. Sow Treatment effect on piglet promotion or demotions during days 0 thru 4. Percent piglets per Treatment per litter that were promoted (moved up one or more quadrants on the udder), or demoted (moved down one or more quadrants on the udder) on treatment days 0 to 4. Treatments (VIB, vibration, n = 16 litters; CONV, hand slaps, n = 17; VIB+EI, vibration followed by electrical impulse, n = 19) were applied twice on day 0 at 1600 and 1800 h, and 4 at 1600 and 1800 h, and once on days 2 and 3 at 1700 h. Nursing bouts were videoed and analyzed by one observer three times per day; 1 (2401-0800), 2 (0801-1600), 3 (1601-2400). Piglets suckling conventionally treated sows tended to be promoted at a higher percentage during the second observation on day two relative to treatment than any other observation within the first four days $P = 0.01$. Piglets suckling VIB+EI treated sows were promoted at a lower percentage during the late observation on day 1 relative to treatment and the early observation on day three relative to treatment $P = 0.01$. The second observation on day 4 relative to treatment for the VIB+EI sows tended to have fewer piglets promoted than all other observations within that treatment category $P \leq 0.10$. Piglets suckling sows treated with VIB+EI were demoted more on the first observation during day one relative to treatment and demoted less on the third observation on day two relative to treatment than other observation times and days $P = 0.008$. There were no significant Treatment x Time interactions ($P > 0.10$) for pigs that stayed within the

same quadrant during days 0-4. LS-means Sliced Time x Treatment Tukey-Kramer adjusted *P*-values *≤ 0.05 and #≤ 0.10.

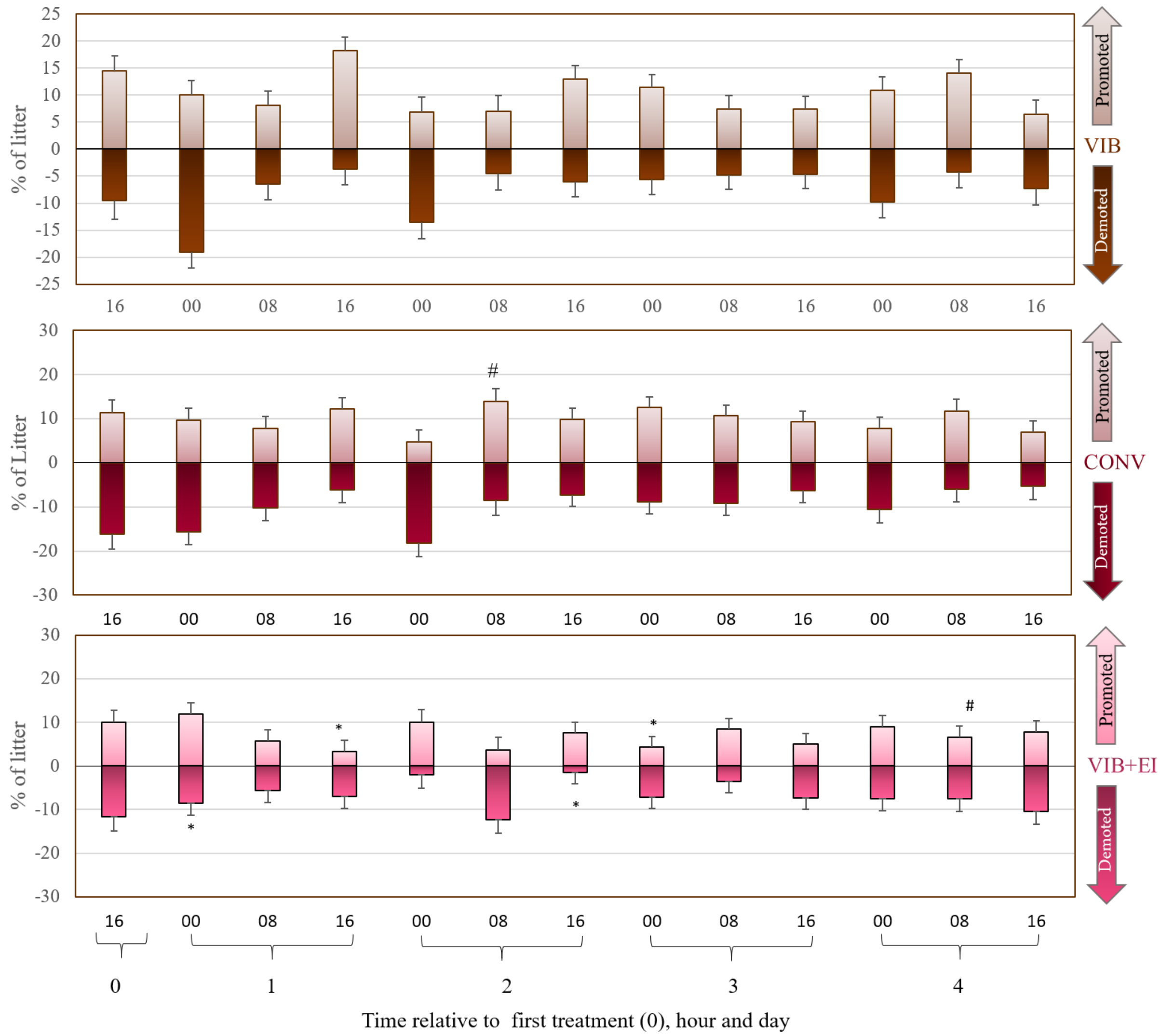
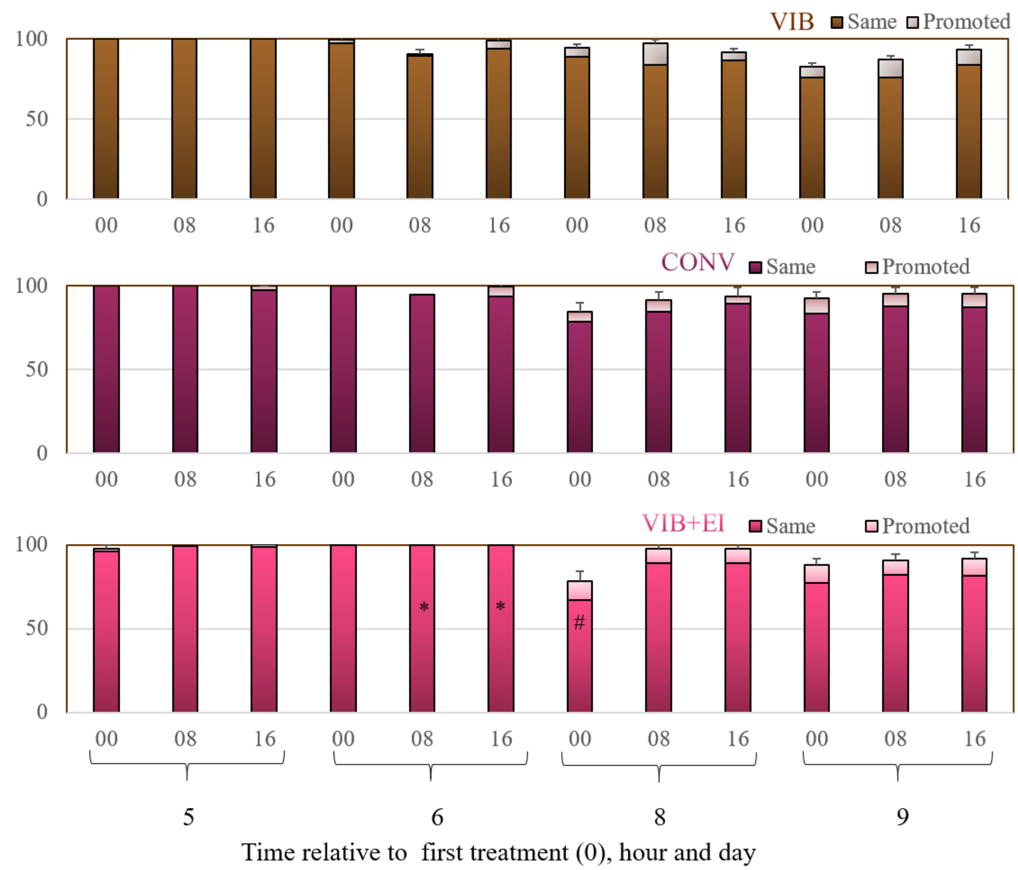
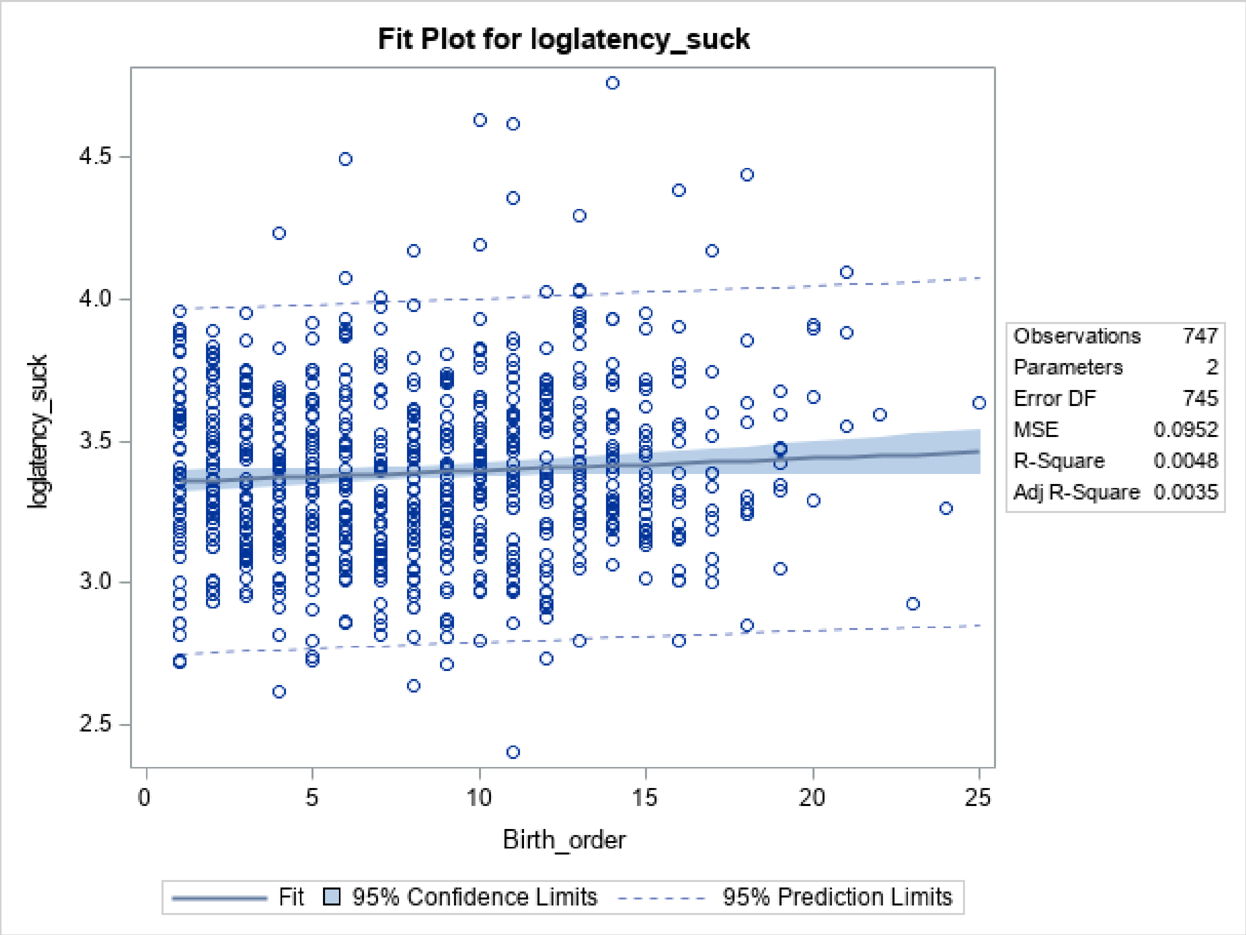


Figure 3.9. Treatment by time effect of quadrant suckled for days 5 thru 9. Percent piglets per group per litter that chose the same quadrant as previously observed (including no teat selected) or were promoted (moved up one or more quadrants on the udder) post treatment days 5, 6, 8 and 9. Video samples of nursing bout measures collected at 0000, 0800, and 1600 h. Piglets suckling sows treated with VIB + EI remained at a consistent teat more during the second and third observations on day six relative to treatment than any other day. Piglets suckling sows treated with VIB+EI chose the same teat quadrant to suckle at a lower percentage on the first observation on day eight relative to treatment than other observations (*P* = 0.018). More piglets were promoted for each treatment, at every observation on days eight and nine relative to treatment than any observation time on days five and six *P*= 0.045. There were no significant Treatment x Time interactions (*P* >0.10) for pigs that were demoted within the same quadrant during days 5-8. LS-means Sliced Time x Treatment Tukey-Kramer adjusted *P*-values *≤ 0.05 and $^{\#}$≤ 0.10.



Supplementary Figure 3.1. Regression analysis of latency to suckle and birth order. The regression analysis of birth order on latency to suckle indicates a tendency for birth order to impact the latency for piglets to suckle *P* = 0.058. The X axis (Birth_order) indicates the birth order of each individually identified piglet. The Y axis (loglatency_suck) represents the natural log transformation of the latency in seconds for each piglet to latch and suckle at a teat. For each ensuing piglet in the birth order the latency to suckle increased. The regression equation, with time in seconds, is $y = 72.2x + 2705.75$ with an adjusted R^2 of 0.006. The regression equation in the figure uses log transformed data, the written equation shown indicates latency in seconds from untransformed data.



Chapter 4 - Reducing piglet mortality with technology

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Introduction.

Preweaning mortality constitutes the largest proportion of animal loss in the swine production system. Various attempts to decrease preweaning mortality have been implemented over the years. For the purposes of this review the following implementations will be regarded as technologies. In todays society it is difficult to break the connotation of technology having something to do with computers or electronics. Whereas the dictionary definition of the word states that technology is the application of knowledge for practical ends. Therefore, implementations in pork production that pertain to the decrease or potential decrease in preweaning mortality will be considered technologies. The following review will discuss technologies such as farrowing environment (crate, pen, etc), introductions to the environment (supplemental milk, supplemental heat, etc), and human intervention (round the clock monitoring, cross fostering etc).

Sus scrofa (wild boar) maintain stable populations on every continent except Antarctica (Barrios-Garcia and Ballari, 2012; Wehr, 2020). These populations exist beyond the limits of domestication as we see in the commercial pork production sector and will be briefly discussed for comparison purposes as modern technologies are not applied to their production. Litter size in wild pigs sampled from the state of Texas in the late 1990's averaged four to six fetuses depending on the age of the female sampled (Taylor et al., 1998). A later estimation in Europe in 2003 found litter size as estimated by fetal presence at harvest to be 6.7 ± 2.1 (Náhlik and Sandor, 2003). Bieber and Ruf (2005) reviewed European literature and noted litter size of wild boar between one and thirteen with average litter size based on quality of environment and sow age ranging from 3.5 to 6.8. More recently, Andersson et al. (2011) studied the reproduction of wild boar and found that litter sizes vary from one to twelve piglets with a mean of 4.8. The estimated preweaning mortality of this Swedish survey data that includes wild boar raised in large natural enclosures is 29.1% (Andersson et al., 2011). The four most commonly reported causes of preweaning mortality were: 1) non-maternal infanticide (36%), 2) piglets being stepped or laid on (27%), 3) predatory loss (18%), and 4) maternal infanticide (15%; Andersson et al., 2011). Náhlik and Sandor, (2003) estimated neonatal mortality in the first two weeks of life at up to 60%. It is to be noted that the population Studied by Andersson et al., (2011) included wild boars in enclosures of approximately 10 ha of area (Andersson et al., 2011), whereas the Náhlik and Sandor (2003) study included population ranges of 6000 – 15000 ha. The biological range of wild boars per GPS tracking in northern Texas USA is 15.13 ± 3.49 km^2 with a core area of 3.14 ± 0.69 km^2 (Franckowiak and Poche, 2018). The large territory traveled by wild boar lends caution to the infanticidal mortality results of Andersson et al., (2011), as sows may have been unnaturally overlapped in terms of habitat. However, the behavioral repertoire of wild boar has animals existing in small family groups of related females so potential overlap of animals is not out of the question. In terms of natural behavioral processes undertaken by the sows to limit the mortality of their young, the most prominent is isolation. Shortly before giving birth the sow will isolate from the rest of the group and find a secluded area that is largely protected from the elements if available where they will dig a 'nest' and give birth (Graves, 1984). The nest usually consists of a concave depression dug into the soil, or a pile of soil and surrounding vegetation that the sow will then dig a depression in the middle of with her nose to lie down (Graves, 1984). The nesting habits of wild boar count as instinctual and natural additions to mitigate preweaning mortality. The purpose of nests being to shelter piglets from the elements and predators (Mayer et al., 2002). However, when needing to utilize swine as a food source or means of income from their production, more advanced tactics to reduce preweaning mortality must be employed.

Sow housing.

One step above feral swine in the production system is outdoor farrowing. This can be done a multitude of ways. Commonly known as ‘huts’, small shelters from the elements are placed in outdoor pastures which sows can use to escape and isolate for farrowing. The premise of which is to decrease preweaning mortality. Like the nest that is previously discussed, the hut adds a level of protection from the elements, as well as containing the piglets from leaving the farrowing site before they are prepared to do so. The containment being done with various designs called ‘fenders’ that act to confine piglet to the hut (Johnson and McGlone, 2003). Huts are known by many names or designs, six of which are seen in Honeyman et al., 2000, (Figure 1). Analysis of the preweaning mortality in all hut types indicated that smaller huts yielded more piglet crushing (Honeyman et al., 2000). Total piglet mortality in outdoor communally housed sows with the opportunity to utilize farrowing huts ranged from 3.7 – 21.6 percent with number born alive at 8.2 – 9.9 pigs per litter (Honeyman et al., 2000). It is to be noted that gilts were used for this study, and there were differences in the interior of the farrowing huts such as sharply sloping wall, or guard rails to offer piglet escape from crushing by the sow. Baxter et al., (2012) reviews five separate categories of farrowing systems with piglet’s mortality rate for outdoor farrowed piglets at 17 or 20% based on slight variations in the system. In this review, Figure 2 illustrates the wide variation in farrowing and lactation systems based on space allowance for the sow, and the ensuing variation in mortality rate per system. The preweaning mortality results of gathering sample data for different space availability to sows at farrowing indicate a small positive correlation (R^2 = 0.097, Figure 2). This indicates that as sow space availability increases, so does preweaning mortality. The difficulty in maintaining production levels at the necessary threshold to meet consumer requirements with outdoor production systems becomes the environment (Baxter et al., 2012). Thus, the pork industry has largely moved to environmentally controlled production indoors, limiting the ability for animals to utilize the amount of space they would desire if available. There are, however, loose housed farrowing options based on indoor operations.

A majority of the data that will include production of piglets from sows which farrow in pens, or are provided excess space, indoors will come from Northern Europe. Switzerland, Sweden and Norway banned farrowing crates for use in swine production (freefarrowing.org). The alternative is therefore pen farrowing which constitutes more space allowance for the sow around the time of parturition. There are a multitude of pen designs and group designs that move sows indoors yet still allow for natural maternal behaviors. These are outlined and described by Baxter et al., (2012). The exhaustive review of literature categorizes 9 separate management tactics that utilize pen or group housing techniques during farrowing (Baxter et al., 2012). Total piglet mortality seen from these various management techniques ranges from 16.4 to 28% (Baxter et al., 2012). Management strategies in which sows are individually held range from 15 to 20.2% piglet mortality (Baxter et al., 2012). Management strategies in which sows are not restricted to one individual, (i.e. communal housing for parturition), the piglet mortality ranges from 19 to 25% (Baxter et al., 2012). It is to be noted, yet not discussed in depth, that management practices are in place to cull sows and genetic lines where infanticide is seen.

When using the pen system, Andersen et al. (2007) saw a decrease in piglet mortality when rails were used to allow the piglets to escape the sow. As crushing by the sow still accounts for the highest percent of piglet losses (Andersen et al., 2007). This combination of utilizing piglet protection rails or bumpers, yet still allowing the sow room to express more natural behaviors is the driver behind maintaining high levels of production and welfare. Singh et al. (2017) found no difference in mortality between pen systems that offer 4.08 m^2 for the sow and crated systems that offer 1.2 m^2 for the sow during lactation. However, both sow groups farrowed in crates that restricted sow movement for the first three days of life (Singh et al., 2017). This coincides with data that indicate the highest incidences of piglet mortality (due to crushing) happen within the first few days of life (Baxter and Edwards, 2018; Weary et al., 1996). Thus, the tradeoff between the welfare of the sow and the welfare of the piglets by decreasing their mortality, seems to be restricting the sow to a crate for the immediate days around farrowing then allowing her increased space up to roughly 4 m^2. The industrialization of swine production is driven by the amount of pork produced per square footage of space utilized. This drives the desire for larger litter sizes and the utilization of space such as to maximize throughput of animals (Baxter et al., 2012). This is done, overwhelmingly by the farrowing crate. Lester Strum, applied for and was granted the first official patent for a “farrowing box”, in 1917 (Strum, 1917). In which an adjustable box for a farrowing sow was able to be manipulated to better fit the dimensions of the sow while she farrowed. In 1963, a United States Patent was granted for a farrowing crate like what we see today to Eide Ingvald. This patent explicitly cites the purpose for this crate as preventing the sow from ‘harming the pigs by laying on them’ (Ingvald, 1963). Examples of various farrowing accommodations and their brief explanation can be seen in Table 1. The latter technological advance being instrumental in the commercialization and industrialization of the swine industry that saw swine production more largely indoors. Piglets are the economical driver of the swine industry. As such their welfare and survival is of the utmost importance in swine production. Given the previous discussion about the increased amount of space and or co-mingling abilities offered to sows, and the piglet mortality rates ranging from 3 to 29%, a farrowing crate becomes a logical solution to garner consistency. There will still be biological variation among sows and piglets that lead to variation in percent mortality. The mortality rate seen in the United States which largely farrows in crates is 13 to 22% for the top and bottom 25% of farms (Stalder, 2017). The comparison between piglet's mortality in farrowing crates and the alternatives that have been previously discussed is present and accessible. In 2019, a meta-analysis of literature directly comparing farrowing crates to farrowing pens was performed (Glencorse et al., 2019). There was a 14% increase in the risk of piglet mortality in farrowing pens compared with farrowing crates (Glencorse et al., 2019). However, the discussion between success of farrowing accommodation does not simply end with the type of sow housing such as outdoor, crate, or pen. Multiple other technologies are applied to pork production in concert with farrowing accommodations to limit preweaning mortality.

Supplemental heat and creep areas for piglets.

Introductions of technology to the farrowing environment are considered here as anything that would go beyond the piglets being born in a nest outdoors. The etiology of piglet mortality is complex and varies over the course of literature (Edwards and Baxter, 2014). Once we reduce the ability for crushing by the sow with the farrowing environment, issues of thermoregulation and colostrum accessibility become limiting factors in terms of piglet survival (Muns et al, 2016 A). Regarding thermoregulation, the goal in commercial piglet production is to create a microenvironment as the critical temp of the sow is lower than that of the piglets. At birth, the lower critical temperature of piglets is 34 to 35° C (Kammersgaard et al., 2011). Whereas the critical temp of the sow, thus, the temperature of the environment the piglet is being born into should be 18 to 20° C (Muns et al., 2016 B). The large discrepancy of temperature to overcome is exacerbated by the small size and lack of thermoregulatory ability of newborn piglets such as brown adipose tissue. Thus, supplementary heat is a requirement to allow for maximum survival rate in production. The means of providing supplementary heat are variable. In 1980, Adams et al., simply observed the presence or absence of heat lamps in litters for the 21-day lactation period. Mortality rates of piglets for the lactation period were 18.5% without supplemental heat lamps and 11% with heat (Adams et al., 1980). Alternatively, there exists technology referred to as a 'heat mat' which radiates heat from the surface that the piglets are meant to lay on. The question as to whether piglets require supplemental heat has long been answered. However, when evaluating the efficacy of a heat mat vs a heat lamp on piglet mortality, Lane et al. (2020) found the mortality rate of 12.3 ± 3.3 when using at heat mat, as opposed to a mortality rate of 15.3 ± 2.5 when using a heat lamp. It is noteworthy, however, that more piglets used the heat sourced from the lamp in the first four days of life than the heat mat (Lane et al., 2020). In terms of variety of heat mats that are available to swine producers, Zhu et al. (2020) evaluated two varieties of heat mat (electric heated or water heated) against an infrared heat lamp in three separate studies. Piglets preferred the water-heated mat to the electric mat or the heat lamp; however, mortality was 22.9% for piglets using the water-heated mat vs 8.9% for piglets using the heat lamp (Zhu et al., 2020). Zhu et al. (2020) found no differences in piglet performance or mortality rate between type of heat mat used. Beyond the temperature of the creep area available to draw piglets away from the sow, brightness of the creep area is also a consideration. To study this, Morello et al. (2019) evaluated two different light levels for the creep area (300 lx vs 4 lx). Despite piglets taking longer to enter the bright creep after birth, piglets spent 7.2% more time in brightly lit creeps than their dark counterparts (Morello et al., 2019). Likewise, for every degree increase in creep temperature, piglets spent 2.1% more time there (Morello et al., 2019). The benefits of increasing heat and type of heat, as in the use of a radiant heat bulb vs an incandescent bulb are also seen in Larsen et al. (2017), where piglets use the creep area heated by radiant heat more and earlier after birth. Vasdal et al. (2010) acknowledges the difficulty in fighting the instinctual drive of piglets to remain near the belly of the sow in a study of three different types of creep areas (bare concrete, bedded concrete, and bedding plus an additional cover). The piglets from the 46 loose housed sows studied showed zero increase in the time spent away from the sow in any of the three creep options (Vasdal et al., 2010). It should be noted that in commercial US systems, bedding is rarely used as the functionality of manure handling systems may be impaired. Some facilities and researchers have taken other lengths to protect piglets from the sow.

Computer and mechanical intervention.

More recent advancements in artificial intelligence and computer learning allow for novel computer technologies to be applied to reduce preweaning mortality. Start-up companies are harnessing this technology and pairing it with auditory studies and sow behavior studies to manually eliminate piglet crushing in farrowing. Piglet vocalizations under distress have been identified and analyzed (Puppe et al., 2005; Linhart et al., 2015). Utilizing proprietary machine learning to identify these distress calls and react via sow stimulation, a system was developed by SwineTech Inc. The utilization of electrical impulse on sows to prevent a piglet from a crushing event is accurately scrutinized. However, the stress and behavioral response of the sows receiving electrical impulse is no greater than that of utilizing hand slaps to get the sow to rise (Mumm et al., 2020). Currently the use of artificial intelligence in this specific avenue has reached approximately 30,000 sows (Rooda, 2021), and company metrics indicate that when properly used in combination with crated systems a 30 % decrease in piglet preweaning mortality can be achieved (Swinetechnologies, 2021).

Other mechanical interventions utilized to keep piglets away from sows do exist as mechanical interventions built into the farrowing environment, beyond simple bumpers or crate sides. Mazzoni et al. (2018) identified the differences in piglets mortality due to crushing in the first three days of life for commercial pigs using two novel crates, compared to traditional farrowing. One novel crate included a slide that removed piglets from the rear of the sow into a heated nest area where they remained until achieving the coordination to walk up the ramp and approach the sow to nurse. The other crate included a lift that, when triggered by the sow standing, raised the sow platform 20 cm above the platform of the piglets. The goal was to prevent the piglets from accessing the space under the sow while she is standing. Piglet mortality due to crushing in the first three days of life in this system was lower for the lifted crates 0.54% vs 2.37%, and 5.46% in slide crates and traditional crates respectively (Mazzoni et al., 2018). An earlier attempt to funnel piglets away from sows toward creep areas was used by Danholt et al. (2011) where a 10% slope was added to the floor of the farrowing pen. The result of this study overwhelmingly indicated that sows prefer to lie of flat surfaces (Danholt et al., 2011). Utilizing computer or engineering technology comes secondary to stockmanship and the intervention of the human caregivers around parturition, and in early life.

Human intervention.

More supervision around the time of parturition decreases both the number of stillborn piglets, as well as mortality of liveborn piglets (Holyoake et al., 1995). A linear decrease in piglet mortality (20.1, 17.0, 16.2, and 13.3 %, respectively) mortality was seen in Norwegian farms that saw their sows at 4 increasing levels of supervision during parturition (Rosvold et al., 2017). The goal of the supervisors at farrowing would be to dry piglets and ensure they are able to thermoregulate effectively to avoid the issues discussed above. Other common intervention tactics around farrowing to allow for decreased mortality and increased performance are management strategies referred to as cross fostering. Crossfostering or transferring takes place in 98% of commercial swine farms (Straw et al., 1998). Social groups mimicked cohorts in terms of weight gain (Canario et al., 2017). Thus, the goal of crossfostering, from a piglet perspective, is to normalize the litters by size. From the perspective of the sow, crossfostering takes place in litters with supernumerary piglet numbers to allow each piglet the opportunity for teat space. When other aspects of piglet vigor and body weight are held constant, the survival of piglets that were crossfostered was higher than non-crossfostered counterparts (Neal and Irvin, 1991). Calderon Diaz et al. (2018) reiterates both the propensity for the use of crossfostering in large commercial farms as 40.8% and 59.2% of piglets crossfostered in the first week of life and in weeks two or later, respectively. Although the reasoning behind crossfostering is to limit mortality by way of standardizing litter size and body weight, Calderon Diaz et al. (2018) found that crossfostered pigs had a greater risk of mortality. Further, it was noted by Vande Pol et al. (2020) that crossfostering, while beneficial in terms of lowering mortality for lightweight piglets when litters are balanced to their benefit; increases the mortality of heavy weight piglets when litters are standardized to their weight. Despite more recent studies that are scrutinizing crossfostering more than in the past, the practice can be beneficial to both sows and piglets and remains prevalent in commercial swine production worldwide. Manipulating the litter sizes and numbers allows a natural avenue of nutrient availability for piglets however, there have been multiple advances in nutrient technology for piglets beyond what is naturally available.

Piglet nutrient supplementation.

The genetic selection for number born alive has in some cases out numbered the functional teats available on the sow, adding further strain to the mortality issue due to starvation. Offering supplemental milk to large litters has been met with mixed results but was revisited by Kobek-Kjeldager et al. (2020) using an automatic milk cup. Kobek-Kjeldager et al., (2020) labeled 19% of their piglets as low suckling success by day 7, yet, 70% of litters had 15 or fewer drinking bouts on the same day. Where sows will naturally suckle piglets up to 20 times/day (Edwards and Baxter, 2014), the sheer number of missed nursing bouts by 19% of the piglets is not made up for by the minimal use of supplementary milk in creep (Kobek-Kjeldager et al., 2020). Recent observational data of three nursing bouts over the course of the day (0001-0800, 0801-1600, 1600-2400) totaling 19,891 individually identified piglet nursing observations indicate that 10.9 percent of piglets miss nursing opportunities (Figure 3; Mumm and Hulbert, unpublished 2020). Recent studies corroborate the fact that significant numbers of piglets miss observed nursing bouts with 9.4 ± 1.20% missing bouts in a study by Schmitt et al. (2019). Despite missing individual nursing bouts, piglet vitality is rarely affected by missing a few nursing bouts over the course of the day, especially later in life. Schmitt et al. (2019) found rearing failures from days 0 to 30 only to be 11.7 ± 3.60%. This number is perhaps artificial and does not coincide with mortality as the researchers removed piglets from the study when welfare was compromised to limit mortality. The mortality of piglets was 7.3 ± 2.7 % (Schmitt et al., 2019).

Summary.

Worldwide pork production is reliant on maintaining or increasing production. The largest portion of loss via mortality in pork production is the lactation phase (Stalder, 2017). Technologies and research efforts are vast and driven towards lowering these preweaning mortality numbers. Not only does this benefit the amount of pork that is produced, it allows for increased welfare of both sows and piglets depending on the technology employed. Whether changes in environment, management or enrichment of housing, production practices, or other technological advances the pork production sector is ever developing towards minimizing preweaning mortality. These developments will require constant scrutiny and manipulation to be utilized in the vastly diverse pork production sector across the world.

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Table 4.1 Examples and explanations of farrowing systems.

Design	Description	Researcher, Date
Farrowing crate	Steel or wooden frame offering approximately 2.0 x 0.5 m (l x w) for the sow to only allow for standing and lying. Piglet area can vary.	Strum 1917; Ingvald 1963
Slide cage crate	A traditional farrowing crate with a sloped floor at the rear of the sow, to allow for piglets to slide into a heated nesting area to better regulate temperature and become more coordinated prior to attempting to suckle.	Mazzoni et al. 2018
Up and down crate	Traditional crate fixed with a trigger that will be moved by the sow when she sits or stands. This trigger raises the sow platform in the crate 20 cm above the piglet platform.	Mazzoni et al. 2018
Ellipsoid farrowing crate	Sow is confined to 1.6 m^2 of total 3.5 m^2 using an elliptical design with steel bars that allows for the sow to turn around.	Lou and Hurnik 1994
Combi-farrowing pen	A pen of 4.7 m^2 total area for the sow and litter uses a traditional adjustable farrowing crate that confines the sow for the desired length of lactation. The crate then hinges open to allow the sow access to the total farrowing pen space.	Moustsen et al. 2013
SWAP pen	Sow Welfare and Piglet Protection pen. Total area of 6.3 m^2, with all but 1.17 m^2 available to the sow while pen is open. The ability to restrict the sow to a more traditional crate design of 1.88 m^2 is available	Hales et al. 2016

	if circumstances call. The restriction is done using swinging bars fixed to a point on the wall.	
Freedom farrowing pen	Total pen space of 5.27 m^2 for the sow. Sow laying area is .8 m wide flanked by 30 cm tall anti crush bars for .9 m in the middle of the pen. The remaining distance is taken up by bars that are .1 m off the ground so the sow can easily step over them to walk, yet laying is uncomfortable.	Gu, et al. 2011

Table 1. Design names and brief descriptions for six researched farrowing accommodations in swine production.

Figure 4.1. Outdoor Farrowing Hut Examples.

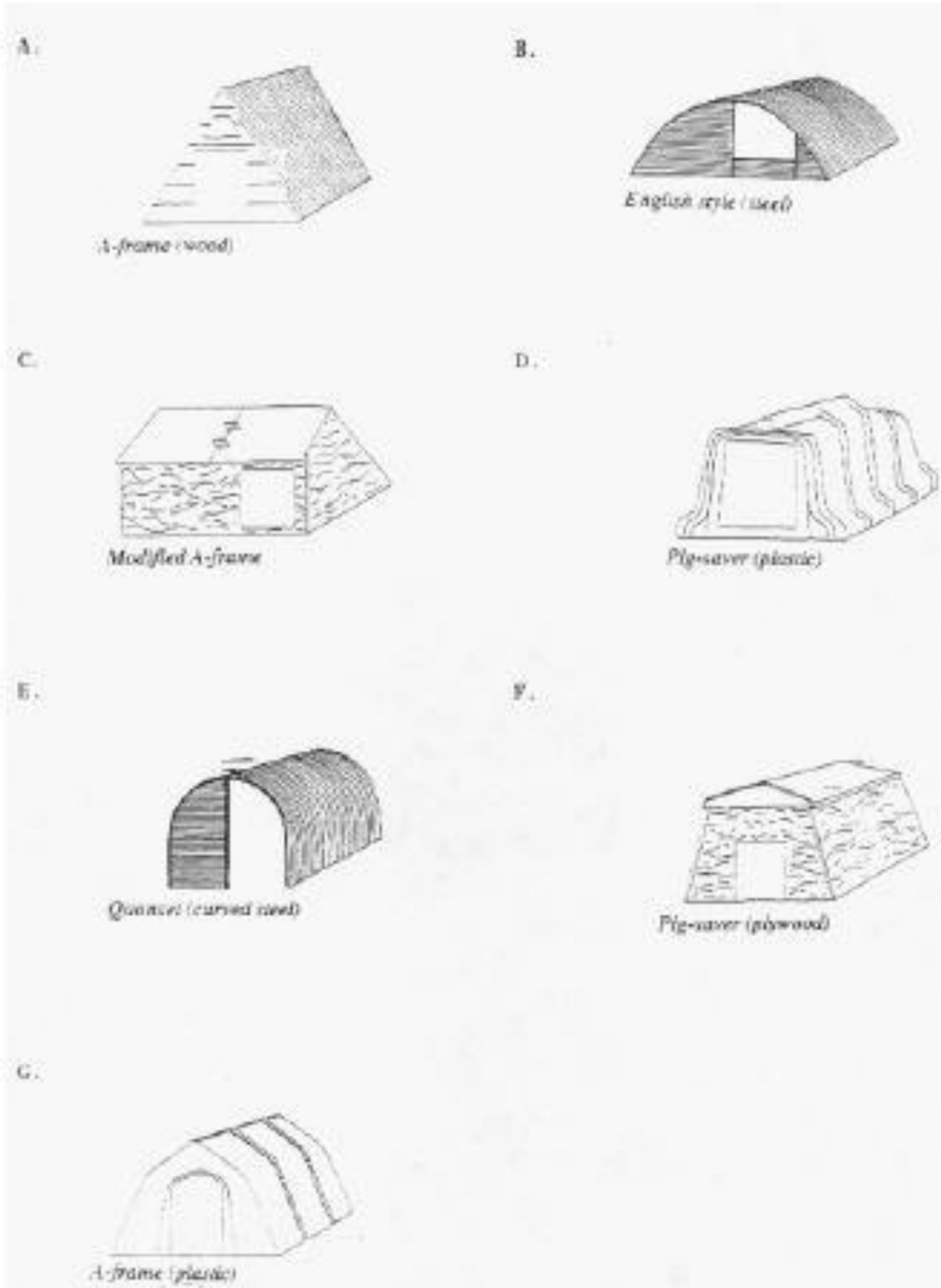
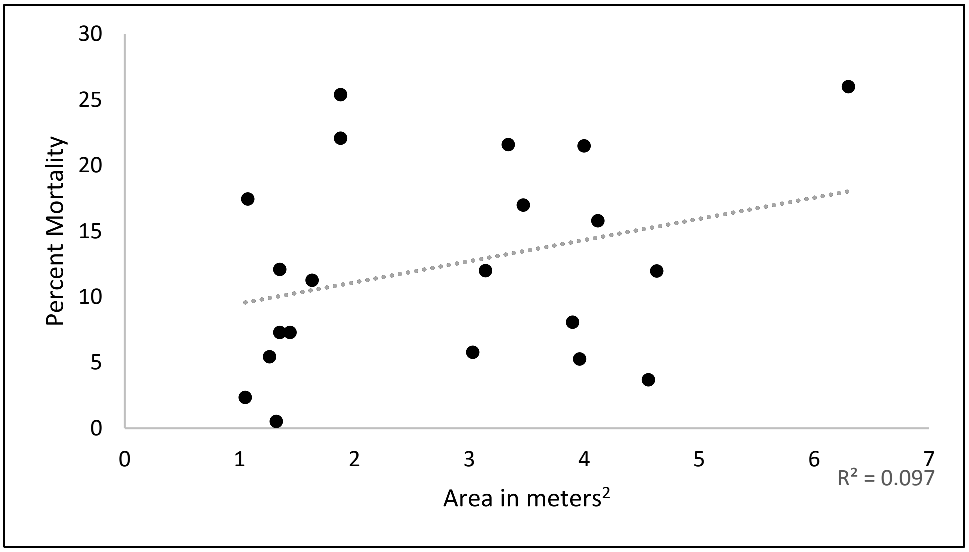


Figure 1 indicates a brief design and the common name of seven outdoor farrowing options as used in the industry. Figure adapted from Honeyman et al., 2000. A: Wooden A-Frame Hut, B: Steel, English Style Hut, C: Modified A-Frame, D: Plastic Pig-Saver Hut, E: Curved Steel Quonset Hut, F: Plywood Pig-saver. G: Plastic A-Frame Hut.

Figure 4.2. Scatter plot of preweaning mortality at given space allowances in literature.



Plot of mortality and available space. Studies where total piglet mortality was given over the course of lactation, along with the total sow space allowance are represented to illustrate the slight increase in piglet mortality as space allowance is increased. X axis indicates area in meters squared. Y axis indicates the mortality over the course of lactation as a percent. The trendline and ensuing R^2 value indicate a tendency for mortality to increase with space allowance for the sow. Data represented in this figure were adapted from (Honeyman et al., 2000; Marchant et al., 2000; Mazzoni et al., 2018; Melisova et al., 2014; Hales et al., 2015; Rangstrup-Christiansen et al., 2018; Schmitt et al., 2019; Vande Pol et al.,