How can we change stalls to better meet our cows' needs? Increasing chain length and stall width to enhance dairy cows' ease of movement and ability to rest in tie-stalls

by

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ABSTRACT

The needs for movement and for sleep are often considered key components of welfare, with severe or prolonged deprivation in one or both likely to have lasting impacts on health and well-being. Environments are often described as central elements defining the capacity of individuals to fulfill these needs, and dairy cows are no exception: unfortunately, common housing systems used nowadays generally restrict the opportunities of movement and the capacity to rest of dairy cows. While tie-stall systems are deemed the most restrictive of all, in general, the presence of stalls in the environment of cows has been associated with altered resting behaviours likely due to some form of restriction in the capacity to rest comfortably. Yet, data available pertaining to the impact of stall systems on the comfort and resting capacity of dairy cows is scarce, especially in the case of tie-stalls, and even results related to some of the more common outcome measures of welfare are punctuated with inconsistencies between studies in terms of results found in the small pool of epidemiological studies available. With the goal of providing more data pertaining to the impact of tie-stall design aspects on the ability of cows to fulfill their need for movement and for rest, we conducted two experimental studies at the Macdonald Campus Dairy Complex. These two studies investigated the impact of increasing chain length beyond the current recommendation and of doubling stall width using 24 and 16 lactating Holstein cows, respectively. Data collected pertaining to stall usage and ease of movement showed that longer chains helped cows feeling more at ease in their environment, but that unlike what was expected, cows with longer chains did not expand their use of space by moving more often outside of their stall at the back end, but rather increased their utilization of the stall front. Double stalls enabled cows to extend their hind legs more often without encroaching onto the neighboring cows' space, and resulted in fewer, but longer lying bouts, akin to what had been previously found in stall-free systems. While the increased ease of movement in tie-stalls with longer chains did not result in a decreased incidence of contacts with stall hardware, the double stall resulted in a significant reduction in the occurrence of such contacts, although no impact was found on the prevalence of injuries. These results show that increasing chain length could represent a low-cost modification to alleviate the restriction on the level of movement imposed to cows in tie-stall systems. Data collected also points towards the need to validate the current recommendations for stall width, while highlighting the potential benefits of providing "special need" cows with a double stall as a periodic measure to aid their recovery by granting them with a more comfortable bed to lie in.

RESUMÉ

Le besoin de bouger et le besoin de dormir sont souvent considérés comme névralgiques au bien-être, un manque prolongé de l'un ou de l'autre étant susceptible d'entraîner des conséquences importantes à court-, voire à long-terme. L'environnement joue un rôle prépondérant dans la capacité d'une personne ou d'un animal à satisfaire ces deux besoins, et à ce titre, la vache laitière ne fait pas exception à la règle. Pourtant, encore aujourd'hui, les systèmes de logement des vaches comportent plusieurs éléments restreignant les opportunités de mouvement et la capacité de repos des animaux, minant potentiellement leur confort. Bien que la stabulation entravée soit considérée comme le système le plus restrictif, la simple présence de stalles dans l'environnement des vaches a un impact sur les comportements de repos, indiquant une forme de restriction imposée aux vaches. Malgré l'importance de la question, très peu de données sont disponibles pour éclairer les producteurs et les autorités sur la question de l'impact qu'a la conception des stalles sur le bien-être des vaches, en particulier en stabulation entravée, où la stalle occupe un rôle clé; les quelques études épidémiologiques disponibles comportent plusieurs contradictions, compliquant toute conclusion formelle à ce sujet. Dans le but de collecter davantage de données sur l'impact qu'a la configuration de la stalle en stabulation entravée sur la capacité des vaches à combler leurs besoins de mouvement et de repos, nous avons conduit deux expériences au complexe laitier du Campus Macdonald de l'Université McGill. Ces deux études visaient à étudier l'impact d'une augmentation de la longueur de la chaîne d'attache et de doubler la largeur de la stalle sur 24 et sur 16 vaches Holstein lactantes. La collecte de données sur l'utilisation de l'espace à la stalle et sur l'aisance de mouvement des vaches a permis de montrer qu'une chaîne plus longue que la recommandation actuelle aide les vaches à être plus à l'aise dans leur environnement et à moins hésiter au moment du coucher. Les vaches n'ont toutefois pas utilisé cette longueur additionnelle pour se déplacer davantage à l'arrière de leur stalle, ayant plutôt augmenté leur utilisation de l'espace à l'avant de celle-ci. Les stalles doubles ont quant à elles permis aux vaches d'étendre leurs pattes plus fréquemment lors du repos, sans devoir envahir l'espace de leurs voisines. Ces vaches ont modifié leurs habitudes de repos à la faveur d'épisodes de repos un peu moins nombreux, mais un peu plus longs, des comportements se rapprochant de ceux observés chez les animaux logés dans des systèmes sans stalles. Alors que l'augmentation de l'aisance de mouvement chez les vaches ayant une chaîne plus longue n'a pas eu d'impact sur la fréquence des collisions avec les éléments de la stalle lors des mouvements de coucher, le fait de doubler la largeur a entraîné une diminution significative de la fréquence de ces contacts. Aucun effet n'a été dénoté sur les blessures. Nos résultats montrent qu'augmenter la longueur de la chaîne peut représenter une façon peu coûteuse de diminuer la restriction imposée au mouvement des vaches logées en stabulation entravée. Les données récoltées montrent que la recommandation actuelle pour la largeur des stalles, commune à la stabulation entravée et à la stabulation libre, devrait être révisée et validée, et que l'utilisation périodique d'une stalle double pourrait permettre à des vaches aux besoins particuliers de récupérer en bénéficiant d'un confort accru à la stalle.

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CONTRIBUTION OF AUTHORS

In this thesis, three coauthored manuscripts are presented.

Authors of manuscripts 1, 2, and 3 (Chapters 2, 3, and 4, respectively) are:

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Véronique Boyer co-conceptualized manuscript 1, conducted the experiments for which the results are presented in manuscripts 2 and 3, analyzed the data, wrote the manuscripts 1, 2, and 3, and assisted with experimental design. Elsa Vasseur supervised the primary author and co-conceptualized manuscript 1, and designed the experiments comprising manuscripts 2 and 3. Elsa also reviewed and co-authored all three manuscripts. Anne Marie de Passillé provided assitance and support with the interpretation of the experiment results and reviewed manuscripts 2 and 3. Steve Adam assisted with the design of the experiments for which the results are presented in manuscripts 2 and 3. Erika Edwards analyzed the data relating to lying postures and contributed ideas and revisions for the experiment presented in manuscript 3. Maria Francesca Guiso analyzed the data relating to lying-down and rising behaviors presented in manuscript 3 and contributed ideas and revisions for the said manuscript. Peter Krawzcel provided revisions for some aspects of manuscript 3.

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CHAPTER 1 – GENERAL INTRODUCTION

The dairy industry represents an important economic stakeholder in Canada, with more than 6 billion $ generated in revenues per year at the farm level, as well as an additional 14.3 billion $ in manufacturing (Canadian Dairy Information Centre, 2017). The sector counts approximately 1.41 million animals, with 969,700 cows (Canadian Dairy Information Centre, 2017) housed within 10,593 farms and producing 89.8 million hectoliters of milk per year (Canadian Dairy Information Centre, 2017). The bulk of the dairy production is located in the provinces of Quebec and Ontario (Canadian Dairy Information Centre, 2017).

73.8% of Canadian dairy farms use tie-stall housing for their animals, a system which has been the object of numerous criticism due to the level of restriction of movement and limited social interactions it imposes to the animals (Veissier et al., 2008; European Food Safety Authority (EFSA), 2009).While concern regarding the welfare of dairy cows increases within the public (Cardoso et al., 2016), the dairy industry has taken steps seeking to ensure an improvement of areas of cow welfare deemed problematic, while maintaining the high milk quality and environmental standards that are relevant as well (Dairy Farmers of Canada, 2015). The approach selected in the ProAction® initiative is oriented around cow-level outcome measures to detect areas of improvement on each individual operation (Dairy Farmers of Canada, 2015). With this certification program, the DFC hope to highlight the work of farmers who are already performing well in terms of animal welfare, as well as to provide information for all dairy farmers to continuously improve the conditions their cows are kept in (Dairy Farmers of Canada, 2015). While the importance of different aspects of housing to the cow is relatively well-known, the currently recommended dimensions for stall systems do not necessarily originate from scientific experiments, or have not been validated to ensure that they represent truly suitable, applicable options for producers to apply with the goal of improving their cows' comfort and welfare. The revision of the Code of Practice, which is also underway, also seeks scientific literature that could provide a base on which future recommendations could be based (National Farm Animal Care Council, 2019), yet these are lacking altogether.

Transitioning away from tie-stall systems before the end of a building's depreciation is likely to have a considerable economic impact on farmers and on the industry as a whole, and seems unrealistic in the short-term (National Milk Producers Federation, 2019). The ProAction® initiative nonetheless aims for producers from tie-stall and free-stall systems alike to put in place measures and modify their facilities or management to continuously improve the welfare of dairy cows (Dairy Farmers of Canada, 2015). To ensure that farmers are sent in the right direction, it is imperative to base future recommendations off options which were tried and evaluated in a rigorous scientific context.

Improvements to housing systems should seek to fulfill cows' needs, in particular for functional space that is adapted to their behavioural requirements. Such behavioural requirements include the need for movement, which is severely impaired in tie-stall systems (Veissier et al., 2008; European Food Safety Authority (EFSA), 2009), and the need for rest, which is of a great importance for dairy cows, both in terms of priority (Cooper et al., 2007; Norring and Valros, 2016) and time allotted (Ito et al., 2009; von Keyserlingk et al., 2012; Nash et al., 2016). Increasing opportunities of movement for dairy cows has been associated with a number of positive outcomes of welfare, including reduced injury levels (Palacio et al, *in prep*.) and improved ease of movement during rising (Palacio et al, *in prep.*) and lying-down movements (Krohn and Munksgaard, 1993; Popescu et al., 2013). Given that stepping activity is present in tied animals (Shepley et al., 2017), it appears possible to alleviate the restriction on the movement of tethered dairy cows, even within the stall in itself, and thus to improve the situation of these animals while they are housed inside. As such, the length of the chain poses as a potential candidate for a low-cost, yet effective modification allowing a tied dairy cow to move more within her environment. Different modifications to the stall could have a positive impact on the capacity of the cow to rest. Recent data showed that current cubicle systems restrict the capacity of cows to choose the orientation and the postures they can adopt when lying down (van Erp-van der Kooij et al., 2019), and contacts with features of the stall are common in both tie-stalls (Popescu et al., 2013; St John, 2019) and free-stalls (Plesch, 2011). Wider stalls were previously associated with increased lying times (Tucker et al., 2004; Bouffard et al., 2017), showing some form of improvement in the cow's capacity to rest, but the underlying causes behind this link have yet to be identified. The occurrence of contacts with stall hardware in stalls offering different amounts of lateral space has not been studied, as only a few authors have gathered data relating to that, despite the theoretical requirements for properly-designed stalls to allow cows to lie down and rise without hitting any element (Anderson, 2019). The impact of wider stalls on other parameters influencing the quality of the cows' rest, such as lying postures, also have yet to be investigated Given the differences observed in resting behaviours and lying postures in stall-free systems, it seems legitimate to question whether stalls even wider than recommended could represent a solution to improve the comfort of dairy cows and provide them with a closer mimic to their natural environment.

1.1 Hypothesis and implications

We hypothesized that cows housed in stalls fitted with longer chains will have and use the opportunity to increase their movement within their environment, and that this would result in an increase in the use of space at the back of the stall, as well as in an increase in the ease of movement of the cows.

We also hypothesized that wider stalls would improve lactating dairy cows' ability to rest, by allowing them to choose more diverse orientations and lying postures. We also anticipated for wider stalls to be associated with fewer collisions with stall hardware during lying-down and rising movements.

1.2 Objectives

1.2.1 Overall objectives

The objective of this research project was to investigate the individual impact of chains longer than the current recommendations and of stalls wider than the current recommendation on the comfort, welfare and behaviour of tie-stall-housed lactating dairy cows. We aimed for our study to bring data aiding in the validation of the current recommendations for chain length and stall width as well.

1.2.2 Specific objectives

There were two specific objectives to this research project: the first was to evaluate whether fitting cows with a chain a deviation longer than the current recommendation improves their ease of movement within their space and increases their movement and use of space. The second objective was to evaluate whether cows installed in stalls of doubled width would modify their resting habits in manners similar to animals in stall-free environments, i.e., employ more diverse lying postures, and change their way of using the space of their stall for resting.

CHAPTER 2 – A REVIEW OF THE IMPACT OF CHAIN LENGTH AND OF STALL WIDTH ON COMMON OUTCOME MEASURES OF DAIRY COW WELFARE

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2.1 Abstract

Given the increased societal concern for the welfare of dairy cattle and the heightened concern of consumers regarding the ability of cows to express natural behaviours, understanding the impact housing systems have on such behaviours becomes of a prime scientific importance. In tie-stall systems, the ability of the cow to express her natural need for movement is largely impacted by tethering, yet no data is available regarding the impact of the length of the tether on the ability of the cow to move. Regarding the ability of the cow to rest, the size of the stall bed, including its width, has been linked with measures of lying time. Current industry recommendations are for the most part not being followed on commercial farms, although improvements seem to have been made in the last decade in terms of compliance. Following the recommendations for chain length appears to aid in reducing injury prevalence and may even aid in maintaining cleanliness of the cows, although inconsistencies between the few studies available are numerous. Wider stalls were associated with increased lying times and reduced prevalence of injuries, although in the case of the latter, data from different studies shows inconsistent results. Overall, collection of data pertaining to the ease of movement of dairy cows housed in stalls with varying lengths of chain and width of stall could provide a greater insight onto how these aspects of stall design impact the welfare of dairy cows by modulating their ability to express certain natural behaviours.

2.2 Introduction

Despite the criticism, tie-stall systems remain common all around the world as housing systems for dairy cattle. In Canada, they encompass for 73.8 % of all dairy barns (Canadian Dairy Information Centre, 2018), while they make up to 75 % of farms in some european countries (Eurostat, 2010; Popescu et al., 2013), and 38.9 % of US dairy barns (United States Department of Agriculture (USDA), 2016). While heavily criticized due to the level of restriction of movement and the limited social interactions in imposes to the animals (Veissier et al., 2008; European Food Safety Authority (EFSA), 2009), tie-stalls are unlikely to disappear overnight (National Milk Producers Federation, 2019), and were shown to be potentially compatible with good levels of welfare, with the implementation of good management practices (Popescu et al., 2013). If the public voices concern over the question of dairy cow welfare (Cardoso et al., 2016), the dairy industry has taken steps seeking to ensure an improvement in areas of cow welfare deemed problematic, while maintaining the high milk quality and environmental standards that are relevant as well, through the use of programs like the ProAction® initiative (Dairy Farmers of Canada, 2015). The approach selected in ProAction (and other alike initiatives) is oriented around common cow-level outcome measures to detect areas of improvement on each individual operation (Dairy Farmers of Canada, 2015). The goal of continuous improvement in welfare of dairy cows brings forward a need for valid, scientific information relative to potential modifications in management practices and/or housing design aspects which could have a significant impact on the ability of the cows to evolve safely and feel comfortable in their environment.

The stall typically refers to an ensemble of structural elements defining an individual lying space for a cow, although even in free-stall environments, they can be used for both standing and for lying (Tucker et al., 2004). In tie-stall systems, the cow is tied at the front of the stall and cannot enter or leave it at will. Her feed is delivered in front of the stall, and a water-providing structure is included, to allow water access at all times. The combination of stall defining elements will determine the amount of longitudinal and lateral space made available to the cow in her stall, and improperly positioned elements can pose as structures hindering the natural movements of dairy cows when transitioning between standing and lying. Housing cows in poorly-dimensioned stalls can also increase the likelihood of injuries (Regula et al., 2004; Zurbrigg et al., 2005a; Nash et al., 2016; Bouffard et al., 2017).

The condition of the cow is likely to impact its ability to move and to rest as well. Lame cows were shown to have altered resting patterns compared to sound cows (Ito et al., 2010), likely due to their reduced movement capacity. Conversely, the provision of exercise or of greater freedom of movement was linked to improvements in indicators of dairy cow ease of movement such as the duration of intention movements prior to lying down (Krohn and Munksgaard, 1993; Gustafson and Lund-Magnussen, 1995) or the duration of the lying-down (Krohn and Munksgaard, 1993; Gustafson and Lund-Magnussen, 1995; Popescu et al., 2013) and rising movements per se (Palacio et al, *in prep*). The presence of stalls themselves were linked with changes in some of these markers of ease of movement (Krohn and Munksgaard, 1993), indicating that some aspects of the stall design may restrict the cows' ability to utilize the space made available to them with ease, or that the space allowed to them does not fully respond to their requirements.

The failure to provide cows with space that fully meets their needs will decrease welfare and may result in various outcomes, including injuries, lameness, and cleanliness amongst the most common ones. Therefore, such indicators can serve to evaluate the impact of different aspects of stall design on different aspects of dairy cow welfare, and to identify which changes should be proposed to producers, depending on the outcome measures deemed as requiring improvements on their farm.

Among the stall design factors, two will be the object of the following literature review, aiming to gather the various information available pertaining to their impact on cow welfare; chain length and stall width, which are presented and discussed in the following sections.

2.3 Chain length and its impact on dairy cow welfare in tie-stall systems

2.3.1 The tie-chain, a tie-stall specific design factor

Chain length is a feature unique to tie-stall housing systems, being the element responsible for keeping the cow from leaving her stall at will (Anderson, 2014) and ensuring that each animal remains in their own assigned space. As such, its length is likely to impact the cow's level of movement restriction, with short chains potentially reducing the cow's ability to move by limiting the amount of space made available to them (Nash et al., 2016). Chains too short can also impede the cow's ability to recline and to rise, and her ability to perform other natural behaviours such as self-grooming and laying with her head resting against her body (Graves et al., 2007; Anderson, 2014). Therefore, the tie chain plays an important role in restricting the movement ability of tied dairy cattle, to a degree of severity dependent on the length allowed. Tethering was shown to disrupt behavioural indicators of comfort and ease of movement, with lying patterns and lying-down movements altered in newly-tied animals compared to loose-housing (Jensen, 1999), suggesting perhaps a frustration of certain behavioural needs associated with tethering. However, the authors provided no detail pertaining to the length of the tether, and other factors such as the softness of the lying surface, known as important to the comfort of the cow and her ease of movement during lying-down motions (Krohn and Munksgaard, 1993; Haley et al., 2000, 2001; Wechsler et al., 2000; Tucker et al., 2009), differed between the tie-stall and the loose-housing treatments. Therefore, these results can hardly confirm whether the chain itself including its length, the fact that the animals were tethered while previously used to stall-free environments, or the other characteristics of the tie-stall treatment were behind the differences observed in the results. Despite that, there is other, more recent data which seems to indicate that there is a behavioural need for movement in dairy cows, as there is a rebound in locomotor activity following a period of confinement in cows habituated to loose housing (Veissier et al., 2008). However, even when tied, dairy cows perform stepping activity, to a level which resembles that of loose-housed animals

(Shepley et al., 2017), indicating a certain level of compensation for the lack of movement in tethered animals. While the quality of the steps performed by cows maintained in tie-stalls is undoubtedly unequal to that of cows in loose housing and pasture systems, this data indicates that the level of movement restriction imposed to the animals, which is determined by the length of the tether, could be mitigated even within the structure of the tie-stall. Improving movement opportunities was linked with increased ease of movement during rising and lying-down movements (Krohn and Munksgaard, 1993; Olmos et al., 2009; Popescu et al., 2013; Palacio, 2016). In light of this, it appears that chain length is stall design factor of a certain importance, due to its central role in modulating the level of movement allowed to tied dairy cattle.

2.3.2 Recommended length of the tether in tie-stalls

Tie-stall systems remain common even as of today, accounting for 73.8% of Canadian dairy farms (Canadian Dairy Information Centre, 2018). Despite that, and despite the important role of the tether in the level of movement allowed to the cow, chain length has received very little attention in terms of scientific research. To our knowledge, the current recommendation for chain length on dairy operations has never been subjected to any controlled-design trial or experimental research aimed to verify its suitability for cows, and chain length itself is only scarcely mentioned in the scientific literature, either for lack of significant results or because it was not an object of investigation in the first place. Therefore, the recommendation is for the time being based off field experience from advisors, who are also providing the principal reasoning behind the numbers they bring forward. The main principles guiding the formulation of the recommendation for chain length can be found in Anderson (2014), who states that a chain of proper length will enable a cow to rest with her head turned back against her body, to groom herself, and to extend her head forward, all while maintaining her safety by limiting her risk of getting a leg caught in the chain. The chain should not interfere with the cow when she lies or when she rises (Graves et al., 2007). The resulting recommendation for chain length thus stipulates that the snap or tie should touch the top of the manger wall (Graves et al., 2007; Anderson, 2014; Valacta, 2014), making its recommended length theoretically dependant upon two other stall parameters, namely manger wall height and tie-rail position. These recommendations themselves are dependant upon cow size (Graves et al., 2007; Anderson, 2014; Valacta, 2014). With all recommendations respected following the body dimensions of an average Holstein cow, this results in a length of about 1 meter

(Lapointe, 2010; Anderson, 2014; Valacta, 2014). Table 2.3.1 summarizes the different recommendations found in the literature currently available.

Table 2.3.1. Summary of the recommendations for chain length found in currently available works of literature

Breed	Specifications regarding age or size	Recommended chain length (cm)	Reference
Holstein	Primiparous cows	96.52	(Anderson, 2014)
Holstein	Adult milking cows	101.6	(Anderson, 2014)
Holstein	Dry cows	101.6	(Anderson, 2014)
Not specified	Cow mass: (A) 455-545 kg (B) 590-680 kg (C) ≥ 725 kg	 (A) 63.5 – 78.7 (B) 78.7 – 94.0 (C) 88.9 – 104.4	(Graves et al., 2007)
Holstein	For the average multiparous lactating cow (HH[1] = 149.86 cm)	99.8	(Lapointe, 2010)
Not specified	Not specified	(0.7 – 0.8 x HH[1]) – 20	(Valacta, 2014)

[1] Hip Height

Table 2.3.2. Chain length as measured on commercial Canadian dairy farms sampled for epidemiological studies on tie-stall design and dairy cow welfare

Province(s)	n cows (n farms)	Breed	Chain Length recorded	Reference
Ontario	(257 farms)[1]	89 % Holstein	Average = 53.3 cm (33 – 114.3 cm)	(Zurbrigg et al., 2005b)
Quebec	4827 cows (118 farms)	97 % Holstein	Average = 57.7 cm (22.7 inches)	(Lapointe, 2010)
Quebec, Ontario	3709 cows (100 farms)	Holstein	Average = 69.4 cm (SD[2] =21.6 cm)	(Nash et al., 2016)
Quebec, Ontario	3485 cows (100 farms)	Holstein	Average difference vs recommendation: QC[3]: - 25.9 cm ON[4]: - 5.1 cm	(Bouffard et al., 2017)
New Brunswick, Nova Scotia, Prince Edward Island	1500 cows (33 farms)	> 80 % Holstein	(A) <50 cm: 14 % of cows (B) 50-79 cm: 60 % of cows (C) ≥ 80 cm: 24 % of cows	(Jewell et al., 2019a)

[1] Includes only farms with tie-rail type of stall design
[2] Standard Deviation
[3] Quebec
[4] Ontario

2.3.3 Current status of chain length on commercial farms: is the recommendation met?

The situation of chain length on Canadian tie-stall farms was assessed on various occasions, with records showing an average length much shorter than the current recommendation in all investigations (Table 2.3.2) : it was of 57.7 cm (22.7 inches) in a sample of 118 Quebec farms (Lapointe, 2010), of 69.4 cm (range: 25 – 130 cm) in a sample of 100 farms from Quebec and Ontario (Nash et al., 2016). From the same sample of farms, it was found that only 7% of Quebec and 39% of Ontario stalls assessed were fitted with a chain that met the current recommendation (Bouffard et al., 2017). A recent study conducted in the Maritime provinces showed that 15% of farms had chains of less than 50 cm, 64% of farms had chains of 50-79 cm, and 21% of farms had chains of 80 cm or longer (Jewell et al., 2019a). While increasing chain length is one of the cheapest and easiest to implement changes, the number of farmers complying to this recommendation remains low (Zurbrigg et al., 2005b; Bouffard et al., 2017). No data could be found relating to the length of the tether on commercial farms in other countries where this type of housing system is still present.

2.3.4 Impact of chain length on outcome measures of welfare

2.3.4.1. Meeting the recommendation for chain length

A recent study collecting data from 100 commercial tie-stall farms from Quebec and Ontario investigated the impact of following the current recommendation for chain length (Bouffard et al., 2017). Their results showed that complying with the current recommendation in terms of chain length results in a 8.3 % decrease in the risk of hock (OR = 0.915 for each 10-cm increase in chain length; $P = 0.002$), a 10 % decrease in the risk of knee lesions (OR = 0.900; $P = 0.001$), and an 8.5 % decrease in the risk of neck lesions (OR = 0.917; $P = 0.024$), with no changes in cow cleanliness recorded (Bouffard et al., 2017). No link was found between chain length and daily lying time. So far, Bouffard et al (2017) was the only study addressing the link between the recommendation for chain length and various outcome measures of welfare, and has shown that respecting or exceeding the said recommendation has positive outcomes on dairy cows' welfare.

With no controlled-design experiment and only a scarce few other epidemiological studies which were all conducted on commercial dairy farms in Canada, the body of literature exploring the impact of chain length on outcome measures of cow welfare is small. These studies have nonetheless reported data pertaining to a few of these outcome measures, namely hock, knee, and hock injuries, lameness, and cow cleanliness. More detailed results on the associations found are presented in the following subsections.

2.3.4.2 Association between chain length and hock injuries

The link between chain length and hock injuries has been investigated only in a few epidemiological studies over the years. The portrait obtained contains several contradictions, with different authors reporting the effect of chains shorter than 50 cm as reducing the odds of hock lesions by 44% (Jewell et al., 2019a; Table 2.3.3), or on the contrary, as increasing them by 1% (Nash et al., 2016), or as having no significant effect (Lapointe, 2010). Longer chains have also been associated with a 1.36 % reduction in prevalence of hock swelling (Zurbrigg et al., 2005a). Despite differences between scoring methods (e.g., severity of swelling not detailed in the scoring sheet vs different levels of swelling resulting in more or less severe injury scores), the studies seem to point towards a positive effect of longer chains in alleviating the risk for injuries at the hock. Authors hypothesized that shorter chains could be linked with increased injuries as they limit the cow's movement within her stall (Zurbrigg et al., 2005a), hindering her ability to rise and to lie down without struggle. This was in turn hypothesized to cause restlessness in cows, increasing the movements of their hind legs during resting bouts, the more numerous movements increasing friction between the lying surface and the skin of the hock and resulting in greater levels of injuries (Zurbrigg et al., 2005a). While this assumption appears plausible, investigation of the cows' capacity to properly transition between the recumbent and the standing posture would have provided a useful insight into the level of restriction experienced by cows with short chains, and could have helped confirm or infirm this potential explanation – such information were not collected nor reported in previous study. Nash et al (2016) reported on the link between hock injury probability and median number of lying bouts, as well as between hock injury probability and median lying bout duration, but did not report on any link between these outcome measures of welfare and chain length. Jewell et al (2019a) was the only study to report a decrease in hock injuries with shorter chain length, a result which is hardly explained at all. The methods employed for injury scoring are similar to those of Nash et al (2016) and Bouffard et al (2017), therefore it is unlikely that the contradictory results obtained are due to a difference in those. However, Jewell et al (2019a) did not provide detail relating to the type of tie-stall installations they surveyed, unlike what was done by Nash et al (2016). Types of tie-stalls other than tie-rail and chain, like the "V" stalls and 2- or 6-bar stalls, are usually fitted with shorter chains, albeit closer to the ground and are therefore not fully comparable in terms of restriction of movement for a given length of chain. Other potential explanatory factors comprise compensatory management (e.g., addition of more bedding) by producers who are aware of the weaknesses of their stalls, something that was mentioned by Jewell et al (2019a) when discussing the link between stall base and risk of injuries, and not in the case of chain length. In all cases, the low compliance to recommendation reported in Canadian farms, for tether length (with chains falling short of the recommendation by about 40 cm) as well as for multiple other factors of stall design, makes it such that impacts of individual stall design factors (i.e., chain length) are more difficult to isolate from the data collected. Other stall design factors may therefore have an impact and could hardly be separated from the outcome measures in such epidemiological studies.

2.3.4.3 Association between chain length and knee injuries

Three studies so far have reported data pertaining to the impact of chain length on knee (or carpal joint) injuries, two of which (Nash et al., 2016; Bouffard et al., 2017) reporting data from the same dataset, collected on 100 tie-stall farms from Quebec and Ontario. Shorter chains put cows at a higher risk for knee injuries, with each 1-cm decrease in chain length associated with a 7% increase in the prevalence of knee injuries (Nash et al., 2016; Table 2.3.3). The third one, which was conducted in the Maritime provinces of Canada using the same injury scoring methods as those described in Nash et al (2016) and Bouffard et al (2017), reported a 40% decrease in prevalence of knee lesions with chains shorter than 50 cm, and an increase of 45% for chains of 80 cm or longer (Jewell et al., 2019a). Much like in the case of hock injuries, this result appears hard to explain, and other elements either pertaining to stall design or to management may again explain the discrepancy between the studies published.

2.3.4.4 Association between chain length and neck injuries

Four epidemiological studies addressed the impact of chain length on neck injuries in dairy cows. Akin to what was found in the case of hock injuries, the reported results differ between studies: one reports an increased risk with longer chains (Lapointe, 2010), another, a 8.3 % decrease with longer chains (OR = 0.917; Bouffard et al., 2017), while the other two found no association between chain length and neck injuries (Zurbrigg et al., 2005b; Jewell et al., 2019a; Table 2.3.3). The discrepancy between results from Lapointe (2010) and Bouffard et al (2017) could lie in the range of measured lengths; while they did not report theirs, Lapointe et al (2010) commented on the fact that in most cases, they did not comply to the recommendation by a considerable margin, a factor which could contribute to the portrait observed. On the other hand, the farm sample of Bouffard et al (2017) contains a known proportion of records where the recommendation for chain length was met, even reporting an increase in the level of compliance in Ontario compared to what had been reported more than ten years earlier by Zurbrigg et al (2005a).

2.3.4.5 Association between chain length and lameness

Two studies collected and analyzed data to evaluate the association between lameness and chain length. The first is Bouffard et al (2017), who collected data from 3485 Holstein cows on 100 tie-stall farms in Quebec and Ontario, and reported no significant link between chain length and lameness. The second study, with data on 1488 lactating dairy cows from 33 tie-stall farms from the Maritime provinces of Canada, did not find any significant association between this aspect of tie-stall design and the prevalence of lameness (Jewell et al., 2019b).

2.3.4.6 Association between chain length and the cleanliness of cows

Literature available showed no significant association between udder cleanliness and length of chain in tie-stall-housed dairy cows (Zurbrigg et al., 2005b; Lapointe, 2010; Bouffard et al., 2017; Table 2.3.4). For hind legs, on the other hand, while most of the data reported goes towards an absence of link between tether length and risk or prevalence of dirty legs (Lapointe, 2010; Bouffard et al., 2017), one study identified a significant association, with each 2.54 cm increase in chain length resulting in a 1.4% decrease in the proportion of moderately dirty hind legs (Zurbrigg et al., 2005a). Prevalence of clean cows on commercial farms in Canada is very high, with only 4.0 % dirty udders, 4.1 % dirty legs, and 10.6 % dirty flanks (Bouffard et al., 2017). While cleanliness may have been one of the justifications given for the short tethers found on commercial farms, with freedom of movement being hypothesized to result in fewer chances for the cow to dirty her stall or her neighbor's stall, it appears that longer chains may on the contrary improve certain aspects of cleanliness, potentially because they allowing the cow to step further back in her stall when defecating. In all instances, results pointing towards an absence of link between cleanliness and chain length or towards a positive impact of longer chains on cleanliness should be put forward as an argument in favour of modifying stalls and fit them with tethers that at least meet the current recommendation.

Table 2.3.3. References exploring the relationship between chain length and hock, knee and neck injuries in tie-stall-housed dairy cattle

Outcome measure	Housing type	Type of study	n cows (n herds)	Breed	Treatments/Associations Investigated	Results	Significance	Reference
Hock injuries	TS[1]	epi[2]	17893 cows (317 farms)	89 % Holstein	Association of hock swelling with chain length	OR[3] = 0.9864 for each 2.54 cm increase in chain length	$P = 0.009$	(Zurbrigg et al., 2005a)
	TS	epi	4827 cows (118 farms)	97 % Holstein	Association of hock injuries with chain length	No association found	NS[4]	(Lapointe, 2010)
	TS	epi	3709 cows (100 farms)	Holstein	Association of hock injuries with chain length	OR = 1.01 for each 1 cm decrease in chain length	$P = 0.03$	(Nash et al., 2016)
	TS	epi	3485 cows (100 farms)	Holstein	Association of hock lesions with chain length	OR = 0.915 for each 10 cm increase in chain length	$P = 0.002$	(Bouffard et al., 2017)
	TS	epi	1455 cows (33 farms)	> 80 % Holstein	Chain length: (A) < 50 cm (B) 50 – 79 cm (C) ≥ 80 cm	(A) OR = 0.56 (B) REF[5] (C) OR = 1.31	$P = 0.019$	(Jewell et al., 2019a)
Knee injuries	TS	epi	3709 cows (100 farms)	Holstein	Association of knee lesions with chain length	OR = 1.07 for each 1 cm decrease in chain length	$P = 0.01$	(Nash et al., 2016)
	TS	epi	3485 cows (100 farms)	Holstein	Association of knee lesions with chain length	OR = 0.900 for each 10 cm increase in chain length	$P = 0.001$	(Bouffard et al., 2017)
	TS	epi	1495 cows (33 farms)	> 80 % Holstein	Chain length: (A) < 50 cm (B) 50 – 79 cm (C) ≥ 80 cm	(A) OR = 0.60 (B) REF (C) OR = 1.45	$P = 0.026$	(Jewell et al., 2019a)
Neck injuries	TS	epi	17893 cows (317 farms)	89 % Holstein	Association between neck injuries and chain length	No association found	NS	(Zurbrigg et al., 2005a)
	TS	epi	4827 cows (118 farms)	97 % Holstein	Association of neck swelling with chain length	OR = 1.03 with increasing chain length	$P < 0.05$	(Lapointe, 2010)
	TS	epi	3485 cows (100 farms)	Holstein	Association of neck lesions with chain length	OR = 0.917 for each 10 cm increase in chain length	$P = 0.024$	(Bouffard et al., 2017)
	TS	epi	1500 cows (33 farms)	> 80 % Holstein	Chain length: (A) < 50 cm (B) 50 – 79 cm (C) ≥ 80 cm	No association found	NS	(Jewell et al., 2019a)

[1] Tie-stall
[2] Epidemiological study
[3] Odds Ratio
[4] Not Significant
[5] Reference

2.3.4.7 Association between chain length and behavioural indicators of comfort and welfare

Only Bouffard et al (2017) collected and analyzed data pertaining to the link between chain length and daily lying time, to find no significant association. To our knowledge, there are no published studies, experimental or epidemiological, that have examined the link between chain length and other aspects of lying time, namely number and duration of lying bouts. None have looked at other behavioural indicators of cow comfort and well-being, including the ease of movement during lying-down and rising motions either. Such data would have provided a greater insight into the causes underlying the differences identified in the outcome measures presented in the epidemiological studies cited in the previous sub-sections. Their current absence precludes our understanding of the role the tie chain length plays in the results presented above.

2.3.5 Summary

Chain length has been linked in epidemiological studies with a few outcome measures of welfare, namely injuries and cleanliness. For hock and knee injuries, as well as for cleanliness, data points towards a positive impact of longer chains on the prevalence of injuries, although results from different studies contradict each other in the case of hock and knee injuries. Literature shows conflicting results regarding the impact of chain length on neck injuries, with longer chains and shorter chains both identified as aiding in reducing risks of injuries in different studies. Lameness and lying time were not linked with chain length, while no other behavioural indicators of ease of movement were examined to evaluate their association with chain length. Overall, the amount of data available relating to the length of tether and its impact on dairy cow welfare is scarce, with all data collected in the context of epidemiological studies on commercial farms. The main weakness in most of these epidemiological studies can be found in the low compliance with the recommendation for most, if not all aspects of tie-stall design. This complicates the work of isolating the impact individual factors such as chain length have on outcome measures of welfare, and further hinders the capacity to draw conclusions as to whether the current recommendation suffices to meet the cows' needs, or if it could be improved from what it currently is. A controlled-design trial ensuring that recommendations are met for all other aspects of tie-stall design may provide more precise information pertaining to the role of chain length on dairy cow welfare, and may allow for a wider array of measures to be collected, including cow ease of movement measures. This could fill the knowledge gap in aiding our understanding of how chain length impacts dairy cow welfare, and whether chains longer than the current recommendation could further improve cow welfare and ease of movement.

Table 2.3.4. References exploring the relationship between chain length and cow cleanliness indicators in tie-stall-housed dairy cattle

Outcome measure	Housing Type	Type of Study	n cows (n herds)	Breed	Treatments/Associations Investigated	Results	Significance	Reference
Cow cleanliness (hind leg)	TS[1]	epi[2]	17893 cows (317 farms)	89 % Holstein	Association between hind limb cleanliness score and chain length	For each 2.54 cm increase in chain length, prevalence of moderately dirty hind limbs decreased by 1.4 % (OR[3] = 0.9860)	*P* = 0.050	(Zurbrigg et al., 2005a)
	TS	epi	4827 cows (118 farms)	97 % Holstein	Association between prevalence of dirty legs and chain length	No association found	NS[4]	(Lapointe, 2010)
	TS	epi	3485 cows (100 farms)	Holstein	Association between risk of dirty legs and chain length	No association found	NS	(Bouffard et al., 2017)
Cow cleanliness (udder)	TS	epi	17893 cows (317 farms)	89 % Holstein	Association between udder cleanliness score and chain length	No association found	NS	(Zurbrigg et al., 2005a)
	TS	epi	4827 cows (118 farms)	97 % Holstein	Association between prevalence of dirty udders and chain length	No association found	NS	(Lapointe, 2010)
	TS	epi	3485 cows (100 farms)	Holstein	Association between risk of dirty udders and chain length	No association found	NS	(Bouffard et al., 2017)
Cow cleanliness (flank)	TS	epi	3485 cows (100 farms)	Holstein	Association between risk of dirty flanks and chain length	No association found	NS	(Bouffard et al., 2017)

[1] Tie-stall
[2] Epidemiological study
[3] Odds Ratio
[4] Not Significant

2.4 Stall width and its impact on dairy cow welfare

2.4.1 Defining stall width

Stall width can be defined as the distance between the centers of the two dividers which work as the right and left side limits of each individual stall. It is a design feature common to all cubicle housing systems, tie-stall and free-stall alike. In both tie-stall and free-stall systems, the cubicle or the stall is the designated area for the cow to lie down and rest, although it is also used by animals for standing (Tucker et al., 2009). The width of the stall defines the lateral space made available to the cow for standing, lying, and for her lying-down and rising movements, while the structures defining the stall and its width are meant to work as limits guiding the cow's position within the stall and imposing her a single possible orientation, unlike open systems such as pasture, in which cows adopt more various spatial orientations (van Erp-van der Kooij et al., 2019). Therefore, stall width must accommodate for the cow's space requirements for resting, as well as for during the transition movements between her standing and recumbent postures. Dairy cows need more lateral space when performing lying-down movements (up to 180 % of hip width) than while standing (Ceballos et al., 2004). When lying in the narrow postures, with all legs held close to the body, the amount of lateral space dairy cows use is about twice their hip-bone width (Anderson, 2014). Other body postures may require even larger amounts of available space. This information points towards a potential role of stall width in facilitating or, in the case of narrow stalls, hindering lying-down and rising movements as well as the capacity of the cow to rest in a comfortable posture. However, width has to be considered in a slightly larger context, it being that it should account for other factors which may impact the physical availability of the space. The amount of lateral space truly available to the cows is influenced by the design of the elements defining such space. Dividers are usually installed on each side of the stall as means of preventing the intrusion of neighboring animals inside each cow's individual resting space, as well as to prevent diagonal standing and lying, which may increase faeces and urine deposition in the stalls by neighboring cows (Aland et al., 2009; Abade et al., 2015). However, dividers, by influencing the amount of lateral space free of obstacles available for the cow, may also impact lying-down movements (Plesch, 2011), and as such, the cow's capacity to rest. Improperly-designed dividers are also cited as hip injury and entrapment hazards for cows (Anderson, 2016), biding for careful design, or at least, accounting for divider characteristics when defining the distance at which they should be positioned, i.e., the recommendation for stall width, something that was presented in one extension publication (Valacta, 2014).

Recent data shows that cubicles restrict the ability of dairy cows to choose their lying orientation, as well as their ability to use more long and wide types of lying postures at will (van Erp-van der Kooij et al., 2019). Therefore, the width of the stall will likely influence the variety of postures cows can employ while resting, by modulating the amount of space available to position the body and the legs. The impact of available space on lying postures employed by dairy cows has not been studied in numerous occasions, but interesting results can nonetheless be found in a few studies. In one experimental trial relating to free-stall crowding, measures of stall usage were collected on a group of cows, showing that having much more stalls than cows resulted in fewer individuals lying in stalls adjacent to another one already occupied (Wierenga et al, 1985). Examining the lying postures of two cows within that same study showed an increased proportion of time spent with the legs extending away from the body in under-crowding situations, where the cows were lying further away from each other (Wierenga et al., 1985). Although the number of animals evaluated and the lack of statistical analysis preclude from drawing any further conclusions and call for more research to be conducted on the topic, these results provide an insight on the impact of neighboring animals in cubicle systems in general. While dividers may pose as immovable obstacles within the cow's environment, the presence of other animals in close proximity may also impact dairy cows' ability to rest in stall systems. While the impact of wider stalls on the ability of cows to use more diverse lying postures has yet to be studied, the comparison between tie-stall housing and loose-pen housing has been examined recently in dry cows, with results echoing those of Wierenga et al (1985): cows housed in loose pens of recommended size, with a much greater amount of space available to lie down compared to a stall matching the current recommendation, spent 7.34 % more time than their tie-stall counterparts with their hind legs stretched (Shepley et al., 2019). Dry cows housed in loose pens also collided with elements of their environment less often than their tie-stall counterparts (49.87 vs 9.64 %), and while lying time did not differ between treatments (Shepley et al., 2019). Comparison of lying postures exhibited by cows on pasture and in cubicles showed similar results, with cows in pasture adopting more long and more wide postures (i.e., with legs stretched out) than cows in stalls, while stalls with varying types of flooring and of divider design also differed in the lying postures they allowed cows to adopt (van Erp-van der Kooij et al., 2019). While loose-pens and pasture are undoubtedly different from stalls in multiple aspects, these results show that further data should be collected to fully understand the role of stall width on the ability of cows to rest in cubicle systems, and to evaluate the suitability of the current recommendations for stall width in fulfilling the needs of rest of dairy cows.

2.4.2 Recommended stall width in tie-stall and free-stall systems

The recommendation for stall width is generally based on the minimal amount of space a cow requires when lying down. A study using 3-D kinematics found that during the movements made by cows transitioning between the standing and the recumbent postures, they would require at maximum a lateral space equivalent to 1.81 times the width between their two hip bones (Ceballos et al., 2004). When the cow is lying in the narrow position (i.e., with all legs held close to her body), the amount of lateral space she occupies, also referred to as the imprint of the cow, is equivalent to twice (2 times) their hip-bone (or hook-bone) width (Anderson, 2014). This measure of imprint appears to be at the base of the recommendation for minimal stall width in both tie-stall and free-stall systems, in the majority of the cases; it is generally expressed as a ratio of twice the hook bone width (Anderson, 2014, 2016; Valacta, 2014; Table 2.4.1) for a mature lactating cow. This width may be increased to account for the diameter of the dividers employed, to ensure that the net amount of space available is at least of twice the hook-bone width (Anderson, 2014). The guide produced by Valacta recommends an addition of 15.24 cm to this ratio for tie-stall-housed dairy cows, and the further addition of 5.08 cm for both tie-stalls and free-stalls in cases where hip clearance is lacking due to divider design (Valacta, 2014). Only one reference presents recommendations for free-stall cubicle width in function of the average cow’s weight, with a resulting range of 104.14 to 132.08 cm, for animals of 408 to 771 kg (McFarland et al., 2016). While some acknowledgement is made pertaining to the fact that dry cows (i.e., in late gestation) and cows with special needs may need wider stalls (Anderson, 2014), no specific numbers are put forward as to how much more width these cows actually require compared to lactating animals. No experiment has yet investigated the suitability of this recommendation for impaired cows, such as lame cows, which have an impaired capability to move; the measure of Ceballos et al (2004) was collected only on sound animals. Overall, the suitability of this recommendation has not been validated per se in any controlled-design trial.

Table 2.4.1. Summary of the recommendations for stall width found in currently available works of literature

Housing Type	Breed	Specifications Regarding Age or Size	Recommended Width (cm)	Reference
TS[1]	Not specified	Not specified	(2x HW[2]) + 15.24 *	(Valacta, 2014)
TS	Not specified	Not specified	(2x HW)	(Anderson, 2014)
FS[3]	Not specified	Not specified	(0.86 x WH[4])	(Bartussek et al., 2008)
FS	Not specified	Not specified	(2x HW) *	(Valacta, 2014)
FS	Not specified	Not specified	(2x HW)	(Anderson, 2016)
FS	Not specified	Cow mass: (A) 408 – 498 kg (B) 498 – 590 kg (C) 590 – 680 kg (D) 680 – 770 kg	 (A) 104.14 – 109.22 (B) 109.22 – 114.30 (C) 114.30 – 121.92 (D) 121.92 – 132.08	(McFarland et al., 2016)

[1] Tie-Stall
[2] Hook-bone Width
[3] Free-Stall
[4] Height at withers
* Add 5.08 cm if not enough clearance for the hips

2.4.3 Current situation for stall width on commercial farms

Recent data pertaining to stall width is available for both tie-stall and free-stall systems, from North America as well as from other areas around the world. In general, the tie-stalls are built larger than free-stall cubicles. This corresponds to some of the differences between the recommendations for width in tie-stall versus free-stall systems, for example from sources like Valacta, who is providing advisory services for cow comfort in Quebec and in the Maritime Provinces of Canada. Anderson (2014) also commented on the fact that some producers were building larger stalls in newer tie-stall barns, a situation which is reflected in the industry portrait found below (Table 2.4.2; Table 2.4.3.). Recent data from 100 Quebec and Ontario tie-stall farms showed a mean width of 1.93 x Hook-bone width and 1.86 x Hook-bone width in both provinces, respectively (Bouffard et al, 2017; Table 2.4.2). Overall, only 35 % of Quebec stalls and 22 % of Ontario stalls were compliant with the current recommendation (Bouffard et al., 2017). Mean stall width for those two provinces was of 126.6 cm (Nash et al., 2016), which was not sufficient, but nonetheless higher than the average of 121.9 cm measured on Ontario farms about ten years earlier (Zurbrigg et al., 2005b). Level of compliance, which was of less than 10 % in Ontario in the early 2000s, has improved over time, indicating a certain level of awareness amongst producers.

Table 2.4.2. Stall width as measured on commercial dairy farms sampled in epidemiological studies on tie-stall design and dairy cow welfare

Country or Province	n cows (n farms)	Breed	Stall Width Recorded	Reference
Ontario	(257 farms)[1]	89 % Holstein	Average = 121.9 cm (91.4 – 144.8 cm)	(Zurbrigg et al., 2005b)
Quebec	4827 cows (118 farms)	97 % Holstein	Average = 130.56 cm (51.4 inches)	(Lapointe, 2010)
Quebec, Ontario	3709 cows (100 farms)	Holstein	Average = 126.6 cm (SD[2] = 11.1 cm)	(Nash et al., 2016)
Quebec, Ontario	3485 cows (100 farms)	Holstein	QC[3]: 1.93 x HW[4] (SD = 0.18) ON[5]: 1.86 x HW (SD = 0.17)	(Bouffard et al., 2017)
New Brunswick, Nova Scotia, Prince Edward Island	1477 cows (33 farms)	> 80 % Holstein	(A) <120 cm: 17 % of cows (B) 120 – 124 cm: 30 % of cows (C) 125 – 134 cm: 19 % of cows (C) ≥ 135 cm: 34 % of cows	(Jewell et al., 2019a)

[1] Includes only farms with tie-rail type of stall design
[2] Standard Deviation
[3] Quebec
[4] Hook-bone Width
[5] Ontario

In the Maritime Provinces, more than 50 % of tie-stall cows have stalls wider than 125 cm, a dimension nearing the recommendation for an average lactating Holstein animal according to Anderson (2014). Overall, while there is still room for improvement in terms of respecting the current recommendation for stall width in tie-stalls, there seems to have been progress made in the last decade or about. In free-stalls, one study conducted on Germany farms reported a mean cubicle width of 111.7 cm, or equivalent to 88.37 % of the required width for the 25 % largest cows in the herds (Plesch, 2011). There are other studies presenting data regarding the dimensions commonly found on commercial farms (Table 2.4.3.). Average cubicle width recorded was of 112 cm in British Columbia, while in California, it was of 121 cm (von Keyserlingk et al., 2012). Data from other Canadian provinces, namely Alberta, Ontario, and Quebec, showed that width of cubicles in those provinces is slightly higher than in British Columbia, at 117 cm (Solano et al., 2015). In Dutch farms consisting mostly of Holstein herds, about 40 % of herds had stalls narrower than 110.2 cm, and 32 % had stalls wider than 111.5 cm (de Vries et al., 2015), but no reference was given in terms of the body size of the cows in the herds visited. In comparison, the most recent data available, originating from herds in the Maritime provinces of Canada, showed that 80 % of the 40 herds sampled had stalls wider than 120 cm, with 40 % being of 125 cm or larger (Jewell et al., 2019a). Few studies compile data on the age of the installations, which may explain some of the differences seen between regions, even amongst farms consisting mostly of Holstein herds.

Table 2.4.3. Stall width as measured on commercial dairy farms sampled in epidemiological studies on free-stall design and dairy cow welfare

Country, State or Province	n cows or stalls (n farms)	Breed	Stall Width Recorded	Reference
Norway	3459 stalls (224 farms)	Norwegian red	1.14 m [1.05 – 1.20] (SD[1] = 0.02 m)	(Ruud et al., 2011)
Germany	(23 herds)	Holstein	111.7 cm, or 88.37 % of required width for 25 % largest cows [81.70 – 95.55 %]	(Plesch, 2011)
NE-US[2], CA[3]; BC[4]	(121 farms)	Holstein	BC: 112 ± 4 cm [103-122] CA: 121 ± 2 cm [117-124] NE-US: 120 ± 3 cm [115-127]	(von Keyserlingk et al., 2012)
China	(34 farms)	Holstein	120 cm [110 – 126] (SD = 3 cm)	(Chapinal et al., 2014)
Alberta, Ontario	3480 cows (87 farms)	Holstein	115 cm (SD = 5 cm)	(Zaffino Heyerhoff et al., 2014)
Netherlands	(179 farms)	Holstein (88 % of farms)	(A) < 110.2 cm: 40 % of herds (B) 110.2 – 111.5 cm: 28 % of herds (C) > 111.5 cm: 32 % of herds	(de Vries et al., 2015)
Alberta, Ontario, Quebec	(141 farms)	Holstein	117 cm (SD = 6 cm)	(Solano et al., 2015)
New Brunswick, Nova Scotia, Prince Edward Island	(40 farms)	> 80 % Holstein	(A) < 120 cm: 20% of herds (B) 120 – 124 cm: 40 % of herds (C) ≥ 125 cm: 40 % of herds	(Jewell et al., 2019a)

[1] Standard Deviation
[2] Northeastern United States
[3] California
[4] British-Columbia

2.4.4 Impact of stall width on outcome measures of welfare in dairy cows

2.4.4.1 Meeting with the current recommendation

One author reports data pertaining to the impact of complying to stall width recommendation in free-stall systems. With data from 23 German farms and measures taken only on Holstein cows, Plesch (2011) reported evaluating the link between stall width compliance and measures of teat cleanliness, teat tip cleanliness, duration of lying-down movements, percentage of collisions during lying-down movements, and percentage of impaired lying-down movements. All of the analyses resulted in no significant association, save for the case of the percentage of lying-down collisions, for which no valid model could be analyzed with the data set available. However, in the case of the percentage of impaired lying-down movements, Plesch (2011) reported a tendency for a decrease of 2.0 % in the proportion of impaired lying-down movements for each 1 % increase in compliance for stall width ($P = 0.09$). It should be noted, however, that in the case of this study, the percentage of compliance was defined as the proportion of the recommended width for the 25 % largest cows in each herd measured in the stalls at each farm. Compliance varied between 82 and 96 % on all farms, which, following the criteria given in the study (compliance acceptable at 90% of above), results in about 26 % of farms sampled providing adequate cubicle width for their largest cows (Plesch, 2011).

The exercise has also been conducted in tie-stall farms. Bouffard et al (2017) found that meeting or exceeding the current recommendation for stall width resulted in an 11.6 % reduction in the risk for neck lesions, a 14.6 % reduction in risk for lameness (OR = 0.854; $P < 0.001$), a 20.8 % increase in risk for dirty flanks (OR = 1.208; $P = 0.001$), and a 16.6 % increase in risk for dirty hind legs (OR = 1.166; $P = 0.043$). Meeting the recommendation for width was also associated with an increase in lying time of 0.107 ± 0.037 h/d ($P = 0.004$).

Although no controlled-design experiments are available, a number of epidemiological studies report attempting to draw links between the width of the stalls or cubicles and various outcome measures of welfare, including body injuries, lameness, lying time, and cleanliness of cows and of stalls. The details pertaining to these results can be found in the following subsections.

2.4.4.2 Associations between stall width and lying time and measures of ease of movement

Three studies report results regarding the impact of wider stalls on daily lying time in dairy cows. The oldest of the three is an experimental study by Tucker et al (2004), who found a 1.2 h/d increase in the lying time of free-stall cows in cubicles of 132 cm in width, compared to cows housed in 112 cm wide cubicles, although they showed no clear preference for any one of the two stall sizes. It was also found that lying time increased by 42 min/d in 126 cm wide cubicles, compared to 106 cm width (Tucker et al., 2004). Solano et al (2016) collected data from 4790 cows on 141 free-stall barns from Alberta, Ontario, and Quebec, and found that having stalls of 114 cm in width or larger resulted in a lying time increase of 0.33 h/d ($P = 0.016$). Data from 3485 cows from 100 tie-stall farms located in Quebec and Ontario showed that each 10-cm increase in stall width resulted in a 0.107 h/d increase in lying time, but no impact on bout frequency (Bouffard et al., 2017). This data from both free-stall and tie-stall systems shows that increasing the amount of lateral space available to the cows improved the lying times of dairy cows.

The link between a few other indicators of ease of movement during lying-down movements and stall width was investigated in a study collecting data from 23 German farms. The duration of lying-down movements and the percentage of collisions with stall elements during lying-down movements were not associated with cubicle width (Plesch, 2011). The percentage of impaired lying-down movements was found to be reduced by 2.0 % for each increase of 1 % in the compliance level for stall width, although not significantly ($P = 0.09$; compliance defined as the division of the measured stall dimension by the recommended dimension; Plesch, 2011). Such measures of ease of movement, for the lying-down and/or the rising movements, were previously studied in a few instances, showing increased ease of movement in stall-free systems (Krohn and Munksgaard, 1993) and with regular access to exercise (Gustafson and Lund-Magnussen, 1995; Loberg et al., 2004; Palacio, 2016), but were used in very few of the studies relating to stall design. While the recording of such measures may add to the duration of assessments conducted on farms, they can be of use when trying to explain the results obtained with some of the most traditional measures of welfare such a daily lying time. Future studies should consider including indicators of ease of movement, like what was done by Plesch (2011), but additional variables could be recorded as well, including the duration of intention movements prior to lying down, which can be deemed an indicator of hesitation at the moment of lying-down (Krohn and Munksgaard, 1993; Gustafson and Lund-Magnussen, 1995; Loberg et al., 2004). In that regard, the work presented by Plesch (2011) already adds a little more information on the subject of stall width and dairy cow ease of movement, but further enhancements to the amount of information collected on that matter could aid our understanding of how the cows perceive changes in the width of their stalls.

2.4.4.3 Associations between stall width and hock injuries

A number of epidemiological studies have examined the link between stall width and hock injuries, both in tie-stall and in free-stall systems. In the case of all eight studies conducted in free-stall systems, the association between the risk of hock injuries and stall width was never found significant (Table 2.4.4). All results from free-stalls point towards an absence of association between these injuries and the width of the cubicles, perhaps as other stall design factors (such as stall base, bedding type, and bedding quantity) play a greater role in the development and healing of injuries than width does. Since all the data was collected in the context of epidemiological studies, other effects such as the levels of compliance to multiple factors of stall design or aspects relating to the management of the stalls and of the herd may make it difficult to isolate the individual impact of factors such as width in such a context.

Data from tie-stalls has for the most part shown the same portrait as in free-stalls (Table 2.4.4), with the exception of Nash et al (2016), who identified a significant link between the odds of hock injuries and the width of stalls. Their data shows that for very wide cows (hip width of 80 cm), the odds of hock injuries increased with increasing stall width, while odds of hock injuries decreased with increasing stall width for all three other categories of cow width ($P = 0.006$; Nash et al., 2016). An explanatory factor brought forward by the authors was that these wide cows were likely more at risk of being injured due to being bigger and heavier, and as such, may have been purposely placed in wider stalls by well-intentioned farmers trying to aid their recovery by granting them with the widest stalls they had available. Again, the influence of other factors linked to stall design and management on commercial farms may complicate the role of isolating the impact of stall width alone. Overall, in the regard of most data collected so far in these epidemiological studies from two housing systems, data seems to point to an absence of a link between stall width and hock injuries, although more research, this time in a more controlled context, could provide a more definitive answer to that question.

2.4.4.4 Associations between stall width and knee injuries

Injuries to the carpal joints were examined in a smaller number of projects than were hock injuries, but data is available from both tie-stall and free-stall epidemiological studies as well. In free-stalls, Haskell et al (2006) found no association between stall width and the prevalence of knee injuries and swellings, and Jewell et al (2019a) reported no numbers regarding the association between knee injuries and stall width, for no significant link was identified between this stall design factor and this type of injury. In tie-stalls, Nash et al (2016) reported that odds of knee injuries were increased in narrower stalls ($P = 0.01$;Table 2.4.5), while Bouffard et al (2017) reported no significant association. The data from 33 tie-stall farms in the Maritime Provinces showed a 92% increase in the risk for knee injuries with stalls narrower than 120 cm, compared to stalls of width comprised between 125 and 134 cm ($P = 0.014$;Table 2.4.5; Jewell et al, 2019a). The link that appears between stall width and knee injuries in tie-stalls has not been observed in free-stall systems, a difference potentially due to the lack of movement and inexistent ability for the cow to choose her stall in tie-stall systems. Such a difference places an utmost importance on the stall and its design in tie-stall systems, especially given the effect of permanent tethering on dairy cow ease of movement within the stall (Popescu et al, 2013). Narrower stalls may increase the risk for cows to hit the stall elements (e.g. dividers) during lying-down and rising movements (Jewell et al, 2019a), or may force cows to reposition themselves during these same movements to avoid hitting the stall hardware. Repositioning efforts during lying-down movements may take the form of shifting of the hindquarters, putting additional pressure on the carpal joints by increasing the amount of time spent in a kneeling position. As for rising movements, crawling on the knees before or after the initial lunging movement could also be linked to increased risks for knee injuries, as they cause friction between the surface of the stall and the carpal joint. Such behaviours were not examined in any of the studies presented above, but studying their occurrence and association with the width of the stall may provide more answers pertaining to the causation for the link that appears between stall width and knee injuries in tie-stall systems.

2.4.4.5 Associations between stall width and neck injuries

The association between neck injuries and stall width has been examined mostly in tie-stall systems, with only one study reporting data from free-stall farms. Most of the studies found no significant association between stall width and the risk for neck injuries (Table 2.4.6). Only one group reported a significant link, with a 11.6 % decrease in the risk for neck injuries for each 10-cm increase in stall width (Bouffard et al, 2017;Table 2.4.6), which was also mentioned in a previous section. Overall, the discrepancy between the different studies makes it difficult to conclude upon the link between stall width and neck injuries, although most of the data compiled so far points towards an absence of such a significant association. Much like in the case of other injuries, the lack of data from experimental studies renders the link more difficult to isolate from potential confounding factors related to management, which were not part of the measures collected in the case of most studies

2.4.4.6 Associations between stall width and lameness

In tie-stalls, two studies have examined the issue of lameness and its link with stall design – including stall width. There is a certain discrepancy between the results from Bouffard et al (2017), who, as stated in section 2.4.4.1, found a decrease in the risk for lameness with increasing stall width, and those of Jewell et al (2019b), who did not identify any significant association (Table 2.4.7). In free-stalls, none of the epidemiological studies consulted found any association between cubicle width and measures of lameness (Table 2.4.7). Lameness may be influenced by components of the stall which impact the cow's ease of movement, and incidentally, her lying time and its distribution, these measures also being altered in lame cows (Solano et al., 2016). Therefore, the relationship between stall width and lameness, while remaining to confirm due to contradicting results from studies with identical assessment methods (in the case of tie-stall epidemiological studies), likely is complex and subject to multiple confounding factors relating to management as well as to other stall design compounds.

2.4.4.7 Associations between stall width and cleanliness of cows and of stalls

Literature available from free-stall systems shows no association between increasing stall width and the cleanliness of the cows (Table 2.4.8). Whether it is the cleanliness of the flanks (Ruud et al., 2010; de Vries et al., 2015), of the hind legs (Ruud et al., 2010), of the udder (Ruud et al., 2010), or of the teats (Plesch, 2011), no significant link was observed with increasing or decreasing of the lateral dimensions of the cubicles on commercial farms.

In tie-stall systems, on the other hand, it was found that increasing stall width resulted in a higher risk of dirty flanks (Bouffard et al, 2017). For the hind legs, Zurbrigg et al (2005a) and Bouffard et al (2017) present results which contradict each other – the former finding no association while the latter identified an increase of 16.6 % in the risk for dirty hind legs with each 10-cm increase in stall width. This result could potentially be attributed to the progress made in the years between which the two studies were conducted, as Bouffard et al (2017) reported a higher proportion of farms complying to the recommendation for stall width (22 % of Ontario farms) than did Zurbrigg et al (2005a; 10 % of farms). Regarding udder cleanliness, results from Lapointe (2010) identified a 5 % decrease in the risk of dirty udders with stalls of recommended width, while Bouffard et al (2017) found no association between the two measures (Table 2.4.8).

One study presents data relating to the impact of stall width on the cleanliness of cubicles in free-stalls. Data from 3459 stalls (224 farms) used by cows of the Norwegian Red breed allowed to identify an increase of 33% in the risk for soiling of the stall by direct deposition of faeces when width was of 1.13 m or narrower (Ruud et al., 2011). It was also found that the risk for stalls to be soiled by faeces transported in by the cows' feet was decreased by 22 % in stalls of 1.13 m width or narrower, compared to wider stalls (Ruud et al., 2011). The impact of stall width on cubicle cleanliness is very likely linked to differences in use of the stalls by the cows, with more width allowing the cows to stand with all four feet in the cubicle more easily, with a greater chance of bringing fecal material from the alleys than with only two feet in the stall (Ruud et al., 2011). The link between wider stalls and lower risk of faeces contamination appears more difficult to explain, as they theoretically grant cows with a greater opportunity to stand and lie diagonally, something which had been previously associated with defecation in the stalls (Ruud et al., 2011). No such data could be found from research conducted on tie-stall farms, hence the link with increased dirtiness of hind legs and flanks observed in wider stalls by Bouffard et al (2017) remains relatively unexplained and addition of data relative to the cleanliness of the stalls could allow a better understanding of causes underlying this association which was identified.

2.4.5 Summary

The literature available from tie-stall and free-stall epidemiological studies has showed that lying time increases in wider stalls compared to narrower ones. Measures of ease of movement during lying-down movement has also pointed out a tendency for improved ease of movement in cows given access to stalls that better meet their space requirements. While there is data showing a decrease in the risk for lameness as well as for hock, knee and neck injuries in tie-stall-housed cows given wider stalls, contradicting results exist between the different studies that were published on the matter. In free-stalls, data tends towards the absence of a link between cubicle width and the risk for hock, knee, and neck injuries. The portrait is the same for the link between lameness and cubicle width in free-stalls. Results relating to cow cleanliness also comprise a few studies contradicting each other as to the impact of wider or narrower stalls on the risk for dirty hind legs, flanks, udders, and teats. The one study presenting results on the cleanliness of free-stalls appears to show a complex reality in which a greater width contributes to increasing the risk of contamination from feet while decreasing the risk of contamination through defecation. In most cases, the contradicting results from different studies show the limitations of epidemiological studies, where potential confounders reduce the ability to properly isolate the individual role of stall width in determining the risk for body lesions, lameness, and cleanliness. Such studies also often lack the data to provide explanatory factors for the results of the risk analyses they present. Studying the impact of stall width on cow comfort in the context of a controlled-design study could yield results devoid of interactions between different aspects of stall design which may come as a “bundle” in commercial farms (e.g., stalls that are too narrow being often too short as well). Given the role stall width appears to play in improving daily lying time, further studying of the cow’s capacity to rest appears as an important step towards further improving dairy cow comfort and well-being. As such, the addition of data relating to ease of movement during both rising and lying-down movements and of data pertaining to the number of lying bouts and the postures employed during the lying bouts could provide a greater insight into not only the causes behind the improvements observed in lying times, but also into the different behaviours contributing to the risks of injuries which may be improved by the provision of wider stalls to dairy cows.

2.4.6 Tables 2.4.4 to 2.4.8

Table 2.4.4. References exploring the relationship between stall width and hock injuries in tie-stall and free-stall housed dairy cattle

Outcome measure	Housing Type	Type of Study	n cows (n herds)	Breed	Treatments/Associations Investigated	Results	Significance	Reference
Hock injuries	TS[1]	epi[2]	17893 cows (317 farms)	89 % Holstein	Association between stall width and hock swelling	No association found	NS[3]	(Zurbrigg et al., 2005a)
	TS	epi	4827 cows (118 farms)	97 % Holstein	Association between stall width and hock lesions and swelling	No association found	NS	(Lapointe, 2010)
	TS	epi	3788 cows (100 farms)	Holstein	Association between risk of hock injury and width of stalls, for 4 different cow widths: (A) 50 cm; (B) 60 cm; (C) 70 cm; (D) 80 cm	With increasing stall width, odds of hock injuries: (A) Decreased; (B) Decreased; (C) Decreased; (D) Increased.	$P = 0.006$	(Nash et al., 2016)
	TS	epi	3485 cows (100 farms)	Holstein	Association between stall width and hock injuries	No association found	NS	(Bouffard et al., 2017)
	TS	epi	1455 cows (33 farms)	> 80 % Holstein	Association between stall width and hock injuries	No association found	NS	(Jewell et al., 2019a)
	FS[4]	epi	(37 farms)	Not specified	Association between stall width and prevalence of hock injuries and swelling	No association found	NS	(Haskell et al., 2006)
	FS	epi	2982 cows (63 farms)	92 % Holstein-Friesian	Association between stall width and prevalence and severity of hair loss at the hock	Not retained in the final model	NS	(Potterton et al., 2011)
	FS	epi	2982 cows (63 farms)	92 % Holstein-Friesian	Association between stall width and prevalence and severity of ulceration at the hock	Not retained in the final model	NS	(Potterton et al., 2011)
	FS	epi	2982 cows (63 farms)	92 % Holstein-Friesian	Association between stall width and prevalence and severity of swelling at the hock	Not retained in the final model	NS	(Potterton et al., 2011)
	FS	epi	2873 cows (76 farms)	Not specified	Association between risk of hock injury and width of stalls	Not retained in the final model	NS	(Barrientos et al., 2013)
	FS	epi	(34 farms)	Holstein	Association between risk of hock injury and width of stalls	Not retained in the final model	NS	(Chapinal et al., 2014)

	FS	epi	3108 cows (39 farms)	> 80 % Holstein	Association between hock injuries and stall width	No association found	NS	(Jewell et al., 2019a)

[1] Tie-stall
[2] Epidemiological study
[3] Not Significant
[4] Free-stall

Table 2.4.5. References exploring the relationship between stall width and knee injuries in tie-stall and free-stall housed dairy cattle

Outcome measure	Housing Type	Type of Study	n cows (n herds)	Breed	Treatments/Associations Investigated	Results	Significance	Reference
Knee injuries	TS[1]	epi[2]	3788 cows (100 farms)	Holstein	Association between stall width and knee injuries	Odds of knee injuries increased in narrower stalls	$P = 0.01$	(Nash et al., 2016)
	TS	epi	3485 cows (100 farms)	Holstein	Association between stall width and knee injuries	No association found	NS[3]	(Bouffard et al., 2017)
	TS	epi	1495 cows (33 farms)	> 80 % Holstein	Risk of knee injuries with stall width of: (A) < 120 cm (B) 120-124 cm (C) 125-134 cm (D) ≥ 135 cm	(A) OR[4] = 1.92 (B) OR = 0.89 (C) REF (D) OR = 0.98	$P = 0.014$	(Jewell et al., 2019a)
	FS[5]	epi	(37 farms)	Not specified	Association between stall width and prevalence of knee injuries and swelling	No association found	NS	(Haskell et al., 2006)
	FS	epi	3118 cows (39 farms)	> 80 % Holstein	Association between stall width and knee injuries	No association found	NS	(Jewell et al., 2019a)

[1] Tie-stall
[2] Epidemiological study
[3] Not significant
[4] Odds Ratio
[5] Free-stall

Table 2.4.6. References exploring the relationship between stall width and neck injuries in tie-stall and free-stall housed dairy cattle

Outcome measure	Housing Type	Type of Study	n cows (n herds)	Breed	Treatments/Associations Investigated	Results	Significance	Reference
Neck injuries	TS[1]	epi[2]	17893 cows (317 farms)	89 % Holstein	Association between stall width and neck injuries	No association found	NS[3]	(Zurbrigg et al., 2005a)
	TS	epi	4827 cows (118 farms)	97 % Holstein	Association between stall width and neck swelling	No association found	NS	(Lapointe, 2010)
	TS	epi	3485 cows (100 farms)	Holstein	Association between stall width and knee injuries	OR[4] = 0.884 for each 10-cm increase in stall width	$P = 0.008$	(Bouffard et al., 2017)
	TS	epi	1500 cows (33 farms)	> 80 % Holstein	Association between stall width and neck injuries	No association found	NS	(Jewell et al., 2019a)
	FS[5]	epi	3129 cows (39 farms)	> 80 % Holstein	Association between stall width and neck injuries	No association found	NS	(Jewell et al., 2019a)

[1] Tie-stall
[2] Epidemiological study
[3] Not significant
[4] Odds Ratio
[5] Free-stall

Table 2.4.7. References exploring the relationship between stall width and lameness in tie-stall and free-stall housed dairy cattle

Outcome measure	Housing Type	Type of Study	n cows (n herds)	Breed	Treatments/Associations Investigated	Results	Significance	Reference
Lameness	TS[1]	epi[2]	3485 cows (100 farms)	Holstein	Association between stall width and lameness	OR[3] = 0.854 for each 10-cm increase in stall width	$P < 0.001$	(Bouffard et al., 2017)
	TS	epi	1500 cows (33 farms)	> 80 % Holstein	Association between stall width and lameness	No association found	NS[4]	(Jewell et al., 2019b)
	FS[5]	epi	(37 farms)	Not specified	Association between stall width and prevalence of lameness	No association found	NS	(Haskell et al., 2006)
	FS	epi	(78 farms)	Not specified	Association between stall width and risk of lameness	Not retained in final model	NS	(Chapinal et al., 2013)
	FS	epi	(34 farms)	Holstein	Association between stall width and risk of clinical lameness	Not retained in final model	NS	(Chapinal et al., 2014)
	FS	epi	(179 farms)	Holstein (88 % of herds)	Association between stall width and % of lame cows in herd	No association found	NS	(de Vries et al., 2015)
	FS	epi	2670 cows (39 farms)	> 80 % Holstein	Association between stall width and lameness	No association found	NS	(Jewell et al., 2019b)

[1] Tie-stall
[2] Epidemiological study
[3] Odds Ratio
[4] Not significant
[5] Free-stall

Table 2.4.8. References exploring the relationship between stall width and cleanliness of cows and of stalls in tie-stall and free-stall housed dairy cattle

Outcome measure	Housing Type	Type of Study	n cows (n herds)	Breed	Treatments/Associations Investigated	Results	Significance	Reference
Cow cleanliness (flank)	FS[1]	epi[2]	2335 cows (232 farms)	Norwegian Red	Association between cow cleanliness score and stall width	Not retained in final model	NS[3]	(Ruud et al., 2010)
	FS	epi	(179 farms)	Holstein (88 % of herds)	Association between stall width and prevalence of dirty hindquarters	No association found	NS	(de Vries et al., 2015)
	TS[4]	epi	3485 cows (100 farms)	Holstein	Association between stall width and risk of dirty flanks	OR[5] = 1.208 for each 10-cm increase in stall width	*P* = 0.0001	(Bouffard et al., 2017)
Cow cleanliness (hind leg)	FS	epi	2335 cows (232 farms)	Norwegian Red	Association between cow cleanliness score and stall width	Not retained in final model	NS	(Ruud et al., 2010)
	TS	epi	17 893 cows (317 farms)	89 % Holstein	Association between stall width and hind limb cleanliness	No association found	NS	(Zurbrigg et al., 2005a)
	TS	epi	3485 cows (100 farms)	Holstein	Association between stall width and risk of dirty hind legs	OR = 1.166 for each 10-cm increase in stall width	*P* = 0.043	(Bouffard et al., 2017)
Cow cleanliness (udder)	FS	epi	2335 cows (232 farms)	Norwegian Red	Association between cow cleanliness score and stall width	Not retained in final model	NS	(Ruud et al., 2010)
	TS	epi	4827 cows (118 farms)	97 % Holstein	Association between stall width (acceptable or narrow) and risk of dirty udder	OR = 0.95 when stall width corresponds to recommendation	*P* < 0.05	(Lapointe, 2010)
	TS	epi	3485 cows (100 farms)	Holstein	Association between stall width and risk of dirty udders	No association found	NS	(Bouffard et al., 2017)
Cow cleanliness (teat)	FS	epi	1171 cows (23 farms)	Holstein	Association between teat soiling and stall width compliance	No association found	NS	(Plesch, 2011)
	FS	epi	1171 cows (23 farms)	Holstein	Association between teat end soiling and stall width compliance	No association found	NS	(Plesch, 2011)
Cow cleanliness (rear)	FS	epi	2335 cows (232 farms)	Norwegian Red	Association between cow cleanliness score and stall width	Not retained in final model	NS	(Ruud et al., 2010)

Cow cleanliness (belly)	FS	epi	2335 cows (232 farms)	Norwegian Red	Association between cow cleanliness score and stall width	Not retained in final model	NS	(Ruud et al., 2010)
Cow cleanliness	FS	epi	2827 cows (24 farms)	Holstein-Friesian	Association between cow cleanliness and FS design parameters	NS	NS	(van Gastelen et al., 2011)
Stall cleanliness	FS	epi	3459 stalls (224 farms)	Norwegian Red	Risk of stall soiling by defecation with stall width of: (A) ≤ 1.13 m (B) > 1.13 m	 (A) OR = 1.33 (B) OR = 1.00*	$P < 0.01$	(Ruud et al., 2011)
	FS	epi	3459 stalls (224 farms)	Norwegian Red	Risk of stall soiling by feet with stall width of: (A) ≤ 1.13 m (B) > 1.13 m	 (A) OR = 0.78 (B) OR = 1.00*	$P < 0.05$	(Ruud et al., 2011)

[1] Free-stall
[2] Epidemiological study
[3] Not significant
[4] Tie-stall
[5] Odds ratio
[*] Reference point

2.5 References

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2.6 Connecting Text

In chapter 2, we have reviewed the current recommendations for chain length and for stall width, as well as the current situation in the industry regarding these stall dimensions and the level of compliance to those two recommendations. We have also reviewed the available literature examining the role chain length and stall width play as stall design factors on the welfare of dairy cows housed in tie-stall and free-stall systems. There are only a few studies available pertaining to the impact of chain length on some of the more traditional measures of welfare, and none touching on aspects of dairy cow ease of movement within the stall. The addition of studies from free-stall systems allowed for a greater body of literature to be looked at in the case of stall width, with most focusing on the same traditional outcome measures of welfare as in the case of chain length. There are multiple conflicting results between the different epidemiological studies presented, in the case of both chain length and stall width, further complicating the task of identifying the precise role these two stall design factors play in the comfort and welfare of dairy cattle. Furthermore, very few studies have examined variables of cow ease of movement which could provide insight onto the causes underlying the increases or decreases in the risks for the different outcome measures of welfare which are presented in most cases. Neither chain length nor stall width were subjected to controlled-design trials aiming to validate the suitability of the recommendation currently presented to producers by various extension services and experts, and used as a point of comparison in a lot of epidemiological studies investigating the links between these aspects of stall design and risks for various outcome measures of welfare. An experiment isolating the impact of each of these two stall design factors and adding measures of cow ease of movement could aid in better understanding the role and the potential of improvements to chain length and stall width in aiding with dairy cow welfare in tie-stall systems. The following two chapters will present experiments conducted to evaluate, using various outcome measures of welfare, the impact of increasing chain length beyond the current recommendation on dairy cow welfare and ease of movement (Chapter 3) and to evaluate the impact of doubling stall width on the comfort and resting capacity of tie-stall-housed dairy cows (Chapter 4).

CHAPTER 3 – LOOSENING THE TIES WE PUT ON DAIRY COWS – THE IMPACT OF A TIE CHAIN LONGER THAN RECOMMENDED ON THE COMFORT AND EASE OF MOVEMENT OF TIE-STALL-HOUSED LACTATING DAIRY COWS

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3.1 Abstract

Although numerous farms in Canada and elsewhere still use tie-stall housing for their dairy cows, very little information pertaining to cow comfort and behaviour in such systems is available for producers. The main criticism addressed to the tie-stall system often lies in how it restricts the cow's ability to move, by offering a reduced dynamic space to the animal. The objective for this study was to see whether increasing the length of the tie chain provides cows with an improved opportunity of movement, and to measure how it impacts their rising and lying movements and behaviours. Two treatments were tested: the current recommendation of 1.00m (control) and a longer chain, of 1.40m (long). Twenty-four cows (12 per treatment) were blocked by number of parities and stage of lactation, then randomly allocated to a treatment and a stall within one of two rows in the barn for a 10-week period. Leg-mounted accelerometers were used to record lying behaviours, and moments of transitions between lying and standing positions for all cows. The cows were recorded on video for 24h/week using cameras positioned above the stall. These videos were then used to evaluate the rising and the lying movements of the cows on weeks 1, 2, 3, 6, 8 and 10. Of all the transitions indicated in the accelerometer data, six rising and six lying motions were selected at random. These motions were assessed by a trained observer to detect the presence of abnormal behaviours. Differences between and within treatments over time were analyzed in SAS using a mixed model with treatment, week, and block as fixed effects, and with row and cow as random effects. Data from weeks 1 to 3 were grouped together as the short-term effects, whereas those from weeks 8-10 were grouped together as the long-term effects. Week 6 was used as the mid-term assessment for analysis. Multiple comparisons between terms were accounted for using a Scheffé adjustment. Results indicate that duration of intention movements (exploratory head movements made by the cow prior to lying down) is shorter in cows with longer chains (13.6 ± 1.03 s vs 16.8 ± 1.01 s; $P = 0.05$). It was also significantly shorter in the long term compared to the short-term for both treatments (13.3±0.92 s vs 16.9±0.81 s, $P < 0.05$). Average number of lying bouts per day was numerically, but not significantly, higher in the long chain group (13.2±1.09 vs 12.8±1.08; $P = 0.70$). These results suggest that increasing the chain length improves the cows' ease of movement and transitions, although all cows became more at ease in their surroundings with time. It may provide evidence of a potential way to improve the dynamic space provided to cows in tie-stall systems, using a simple, affordable modification.

3.2 Introduction

Tie-stall housing systems for dairy cows have been the focus of numerous criticism, mostly oriented around the restriction it imposes on the cows' ability to move and to engage in significant social activities with herdmates (Loberg et al., 2004; Veissier et al., 2008; European Food Safety Authority (EFSA), 2009; National Milk Producers Federation, 2019). Despite the negative views, tie-stalls remain a fairly prominent housing system in Canada and in the United States, where they respectively account for 73.8 % and 38.9 % of all dairy operations (United States Department of Agriculture (USDA), 2016; Canadian Dairy Information Centre, 2018). European countries also comprise a non-negligible proportion of tie-stall farms, ranging from around 9% to more than 90% of farms (Eurostat, 2010). In a lot of cases, these farms are found in the small or very small farm categories (National Milk Producers Federation, 2019), rendering practices such as pasture access for the cows easier to implement and manage. There is a number of known advantages to releasing the cows from their stalls, including improvements in the ease of movement; measures such a the duration of intention movements prior to lying-down and the overall duration of lying-down movements were found to be improved in dairy cattle granted access to pasture or to an outdoor exercise yard on a regular basis (Krohn and Munksgaard, 1993; Gustafson and Lund-Magnussen, 1995; Popescu et al., 2013). However, one must bear in mind that while releasing the cow from the stall to grant her with a greater amount of obstacle-free space is positive from a welfare perspective, the provision of outdoor access may be limited by climatic conditions in many countries around the world, imposing a number of months of housing without outdoor access (European Food Safety Authority, 2009). During the housing period, the ease of movement of cows has been shown to decrease compared to animals still granted outdoor access on a regular basis (Palacio et al, *in prep*). This difference shows how the configuration of the stall and the capacity of the cow to move can have considerable impacts on her fitness. Yet, no experimental studies have examined the impact of providing different lengths of chain could have on the ease of movement of tied dairy cows, and the current recommendation has never been validated per se. The current industry situation shows that chain length fails to meet the established recommendations, but that improvements on that aspects can be linked with positive outcomes such as decreased odds of knee and hock injuries (Bouffard et al., 2017). This poses a unique opportunity to study the impact of a longer chain on the ease of movement of tied dairy cattle. By doing so, one could provide insight onto the potential of a low-cost modification to improve the capacity of dairy cows to move within their stalls.

The objective of this trial was to investigate the impact of a chain longer than recommended on lactating dairy cows' ease of movement as well as on a number of other outcome measures of welfare. We hypothesized that decreasing the level of movement restriction at the stall through increased chain length would improve the cows' ease of movement and would impact their use of the space made available to them, namely resulting in a greater exploration of their surroundings.

3.3 Materials and Methods

3.3.1 Ethics Statement

The certified Animal Care Committee of McGill University and affiliated hospitals and research institutes reviewed and approved the use of animals in this project and all procedures (#2016–7794). All aspects of this study meet the high standards established by the Canadian Council on Animal Care to ensure the continued humane and ethical use of animals in research.

3.3.2 Cows and treatments

The trial was conducted at the Macdonald Campus Cattle Complex of McGill University, in Ste-Anne-de-Bellevue, Quebec, Canada. 24 lactating cows from the dairy herd (Average DIM 129) were enrolled for a period of 10 weeks beginning on February 20th, 2017, and ending on May 1st, 2017. The cows enrolled for the trials were blocked according to number of parities and stage of lactation, then separated between the two treatments by random draw. The treatments consisted in 1.00 m long tie chain following current recommendations (hereafter, **recommended** length; National Farm Animal Care Council and Dairy Farmers of Canada, 2009; Anderson, 2014; Baillargeon et al., 2014) and of a tie chain of 1.40 cm (hereafter, **long** chain). Body dimensions of the cows were measured prior to the beginning of the trial. The average rump height and hip width were 154.06 ± 3.18 and 67.79 ± 4.64 cm, respectively. Five cows (4 long chain, 1 recommended length) were removed at different points (1 in week 6, 1 In week 8, 2 in week 9, 1 in week 10) during the trial. Reasons for removal include poor temperament and incidents at the stall that made safe manipulation of the animals difficult. Data from the animals removed was removed from analysis as per when they were taken off the trial.

3.3.3 Housing and management

The trial used two rows facing a wall in the Macdonald Campus Dairy Complex. Cows were housed in a stall that was at ±5 cm of the current recommendations for length and width

(National Farm Animal Care Council and Dairy Farmers of Canada, 2009; Anderson, 2014; Valacta, 2014) according to their individual body dimensions. The average stall length and width were 188.3 and 141.1 cm. For all stalls, the tie-rail was positioned as per the current recommendation (National Farm Animal Care Council and Dairy Farmers of Canada, 2009; Anderson, 2014; Valacta, 2014), which corresponds to a height of 48 inches from the stall base, and a forward position of 14 inches from the manger wall. Prior to the beginning of the trial, the average chain length for the two rows was 85 cm. The gutters behind all the stalls in the barn were covered with a grid. The stall base consisted in KKM longline rubber mats (Gummiwerk Kraiburg Elastik GmbH & Co. KG, Tittmoning, Germany) on which a fine layer of sawdust bedding (less than 2 cm) was added once per day, in the morning. Management of the cows in the trial was not altered: cleaning of the stalls and the gutters was done as needed by the barn staff, from 5:00 until 21:00, and in the same manner as it was done in the rest of the barn. Cows were milked twice per day in stall, with the morning milking spanning from 5:00 to 7:00, and the afternoon milking, from 17:00 to 19:00.The herd was fed 4 times daily: one full ration was served in the morning, at 6:00, with a top-up served later in the morning. Another serving of ration was delivered in the afternoon, at 16:00, and the last batch was served in the evening. Cows were fed a TMR consisting of grass and legume silage, corn silage, dry corn, high moisture corn, and protein and mineral supplements. Feed was pushed back 6 times per day by the farm staff. Water was available ad libitum from self-serving water bowls shared between adjacent stalls (1 bowl per 2 cows).

3.3.4 Video Recording

Each cow was filmed 24h per week, using StereoPlus surveillance cameras (Smart Turret 2.8, Hikvision Digital Technology Co., Ltd., Hangzhou, China) installed above the tie-stalls, at a height of 338 cm off the stall surface. The cameras were fitted on rails, which allowed for moving them from one stall to another between the recording hours. Each cow was filmed for a period of 24h on the same day every week with the camera placed in the same position.The observation videos were used to evaluate the cows' movement in the stalls, as well as the quality of the lying-down and of the rising movements of the cows.

3.3.5 Measures

3.3.5.1 Lying time

Lying time was automatically recorded using leg-mounted data loggers (HOBO Pendant G Acceleration Data Loggers, Onset Computer Corporation, Pocasset, MA, USA) previously validated for use in tie-stall settings (Vasseur et al., 2012). The data loggers were secured on the hind leg of each cow using auto-adhesive flexible wrapping bandage (Vet-Wrap, CoFlex®Vet, Andover HealthCare inc, Salisbury, MA, USA) following Vasseur et al (2012), and were switched weekly from side to side to avoid injury. Total lying time in hours/d, average number of lying bouts per day, and average duration of lying bouts, in hours/bout, were computed from the HOBO data using Excel macros (Microsoft Corp., Redmond, WA) for each week.

3.3.5.2 Quality of lying-down and rising movements

Evaluation of the rising and lying events was done through a visual assessment of the observation videos, which was done by one trained observer. The visual evaluation aimed to identify possible issues occurring during the rising and/or during the lying events. Evaluation of 6 lying and 6 rising events per 24h per cow, distributed as 4 events during the day and 2 during the night hours, was determined to be representative of a cow's lying and rising behaviour for a full day and a full week by the means of a validation study done by Zambelis et al (*in review*), during the development of the scoring method. Thus, the observer scored 6 lying and 6 rising events per cow per week, with 4 events of each selected at random during the day hours, and 2 events randomly picked among the night hours events (Zambelis et al, *in review*).

For the evaluation of the lying-down movements, the observer was recording the occurrence of specific behavioural indicators defined in **Table 3.3.1**. For the indicators scored using a binary classification, the proportion of lying-down events in which a score of 1 was recorded was calculated for each week evaluated, yielding a percentage of lying-down events during which the said behaviour occurred. For the evaluation of the rising sequences, the observer evaluated specific behavioural indicators, which are presented in **Table 3.3.2**. For the indicators scored using a binary classification, the proportion of rising events in which a score of 1 was calculated for each week evaluated, yielding a percentage of rising events during which the said behaviour occurred. Inter-observer (across lying behaviours: $K_w = 0.67$; across rising behaviours: $K_w = 0.80$) and intra-observer repeatability (across lying behaviours: $K_w = 0.99$; across rising behaviours: $K_w = 1.00$) assessments were conducted following the scoring of each week.

Table 3.3.1 Description of the lying-down behaviours and sampling units that were evaluated for all cows in all treatment groups[1]

Behaviour	Sampling Unit	Description of Behaviour
Duration of intention movements before lying down (phase 1)	Seconds	Length of time the cow repeatedly and continuously sniffs the lying surface with possible sweeping movements of the head without lying down Start of movement: when sniffing starts End of movement: when phase 2 begins
Duration of lying motion (phase 2)	Seconds	Length of time required to complete the lying motion Start of motion: the cow descends to one of the forelegs End of motion: the whole body touches the ground; body is stable
Contact with environment	Yes (1) or no (0)	Cow comes into contact with dividers and/or tie-rail during the lying motion.
Attempts of lying	Number of attempts	The number of attempts required to successfully complete the lying motion Failed lying attempt: Cow stands up after the start of a lying down motion (goes on one or both carpal joints and then back up onto hooves)
Hind quarters shifting	Yes (1) or no (0)	When on carpal joints, cow does multiple shifting motions with its hind quarters before lying down completely (≥ 3 sec)
Dog-sitting	Yes (1) or no (0)	Cow lies down with hind quarters first and then goes down on carpal joint
Lying on left or right	Left (1) or Right (0)	Direction the hind legs point when cow is lying (based on technician viewing cow from above)
Overall Abnormal Lying	Yes (1) or no (0)	Cow requires > 1 attempt to lie down and/or is scored as 'Yes' for contact with the tie-rail, hind quarter stepping, and/or dog-sitting

[1]Based on Zambelis et al (*in review*)

3.3.5.3 Tracking of the cow's movement in the stall

Tracking of the cow's movement within their stalls was done using images taken from the observation videos recorded by the cameras positioned above the stalls. Images were extracted from the 24h video files of weeks 1, 2, 3, 6, 8 and 10 at a rate of 1 photo per minute of video, for a final number of 1441 images analyzed per cow per week. The images were analyzed using the manual tracking plugin of the FIJI ImageJ software, following Zambelis et al (*in progress*). In this method, 3 points on the cow are followed on each image: the tip of the left hip, the tip of the right hip, and the base of the neck (see **Figure 3.3.1**), allowing to infer the position of the cow in or out of the stall parameters. The stall parameters were defined considering the optical deformation due to the position of the camera above the stalls, to ensure that cows would not be considered as outside of the stall while they were still inside the parameters.

Table 3.3.2. Description of the rising behaviours and sampling units that were evaluated for all cows in all treatment groups[1]

Behaviour	Sampling Unit	Description of Behaviour
Duration of rising motion	Seconds	Length of time required to complete the rising motion Start of motion: cow is in sternal position, situated to propel itself forward End of motion: cow gathers its forelimb side by side on the stall bed.
Contact with tie-rail	Yes (1) or no (0)	While cow propels itself forward (with both carpal joints on the ground), its head or neck touches the tie-rail.
Backward movement on carpal joints	Yes (1) or no (0)	When resting on carpal joints, cow moves its front leg(s) backwards before or after propelling itself
Delayed rising	Yes (1) or no (0)	Cow rests on carpal joints for > 10 s
Attempts of rising	Number of attempts	The number of attempts required to successfully complete the rising motion Failed lying attempt: Cow propels itself forward from sternal position without successfully rising; can appear as a forward and back motion
Horse rising	Yes (1) or no (0)	Cow gets up first with front legs, then with hind legs
Overall abnormal rising	Yes (1) or no (0)	Cow requires > 1 attempt to rise and/or is scored as 'Yes' for contact with environment, backward movement on carpal joints, delayed rising, and/or horse rising

[1]Based on Zambelis et al (*in review*).

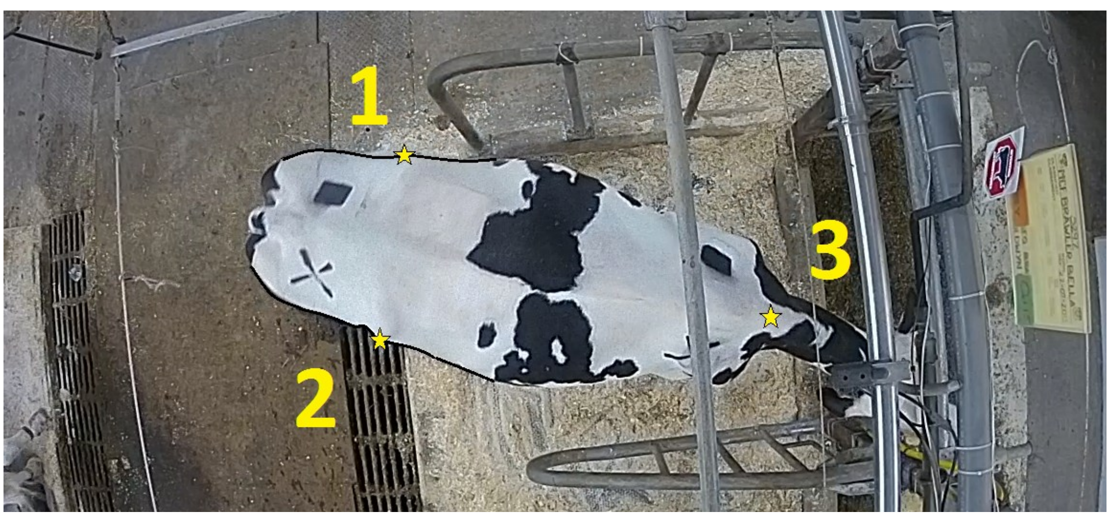

Figure 3.3.1. The three body points (parts) manually tracked on the cows. 1 represents the tip of the left hip bone, 2, the tip of the right hip bone, and 3 is the base of the neck (withers)

Using Excel sheets and Excel macros (Microsoft Corp., Redmond, WA), the percentage of time spent by each point outside of the stall was computed and the distance of each point found outside of the stall parameters were calculated. The final variables analyzed were, for the left and right hip body points: time spent outside of the stall (% of daily time; indicative of use of space at the back and on the sides outside of the stall), maximum distance outside the stall (cm), minimum distance outside the stall (cm), average distance outside the stall (cm). Final variables analyzed for the withers body point were: time spent outside of the stall (% of daily time; indicative of use of the manger area space, outside of stall), maximum distance outside the stall (cm), minimum distance outside the stall (cm), average distance outside the stall (cm).

3.3.5.4Clinical signs and stall cleanliness

Two trained observers conducted a visual assessment of injuries on seventeen different locations found on the cow's body, neck, front legs, and back legs, on both sides. The method, adapted from methodologies described in Gibbons et al. (2012) and in Brenninkmeyer et al. (2016), consisted in a detailed recording of the injury types (nothing, broken hair, bald spot, white scab, red scab, open wound, minor swelling, medium swelling, major swelling) present on each of the locations. The detailed injury types were then categorized on a scale of 0 to 4 according to the degree of severity, 0 = No injury, or nothing, and 4 = Open wound and/or Major swelling present. When more than one type of lesion was present, the most severe lesion or swelling score for the area was retained as the final score for the area. For analysis of injury scores, the score differences from the baseline (week 0) were used as the outcome measures, because initial state of injury of animals when they were enrolled in the trial could not be accounted for in the experimental design (i.e., cow selection). Inter-observer (overall average K = 0.79, across all locations) and intra-observer (overall average K = 0.84, across all locations) repeatability assessments were conducted on weeks 1, 6, and 10.

Body condition score, cow cleanliness, and stall cleanliness and bedding quantity were assessed following procedures found in Vasseur et al (2013, 2015) and found on the Dairy Research Portal (https://www.dairyresearch.ca/cow-comfort.php#self).

Each cow's body condition score was assessed live by the same trained observer once per week except on week 5, using a 5-point scale system with increments of 0.25, where a cow that was scored at 2 or below was considered as severely underconditioned, and a cow that was scored above 2, as adequately conditioned. Intra- (overall average $K_w = 0.82$) and inter-observer (overall average K_w = 0.74) repeatability was evaluated at the beginning, in the middle and at the end of the 10-week period.

The cleanliness of the lower leg, flank and lower udder regions were visually assessed once per week by one trained observer. Each area was scored on a scale of 0-3 and categorized as clean (scores 0-1) or dirty (scores 2-3). The proportion of cows with clean legs, clean flanks, and clean lower udder region in each treatment group was calculated each week. Inter-observer (overall average K_w = 0.74; 98% agreement between observers) and intra-observer (overall average K_w = 0.40; 96% agreement between observers) repeatability was assessed at the beginning, in the middle and at the end of the 10-week period.

The cleanliness of stalls and the quantity of bedding in the stalls was assessed twice per week, Thursday afternoon at 4:30, and Friday morning, at 4:30, to evaluate the stalls before they got cleaned by the farm staff. The cleanliness of each stall was scored on a scale of 0-4 and classified as clean (scores 0-1) or dirty (scores 2-4), and the depth of bedding of each stall was assessed, with a layer of bedding of 2 cm or thinner being scored as “little” (L), and more than 2 cm as “deep” (D). The two measures collected for each stall were used to calculate the proportion of clean stalls per treatment for each week, as well as the proportion of stalls with deep bedding per treatment for each week. Inter-observer (overall average K_w = 0.74; 98% agreement between observers) and intra-observer (overall average K_w = 0.40; 96% agreement between observers) repeatability was assessed at the beginning, in the middle and at the end of the 10-week period.

Lameness was assessed once weekly by two observers, using video recordings and following Stall Lameness Scoring (SLS) methods adapted from Leach et al. (2009), and described in further detail in Palacio et al. (2017) and Gibbons et al. (2014). Each cow was filmed standing from 3 different positions for a minimum of 10 seconds per side. Following that, the cow was then encouraged to move from one side to the other a few times. For each video, the observers recorded whether each of the four following behaviours were present or absent: 1. Standing on the edge (Edge): the cow positions one hoof (or both hooves) at the edge of the stall surface. 2. Resting of one limb (Rest): the cow rests one foot while standing still, indicated by a partial or a complete lifting of the foot off the ground. 3. Weight shifting (Shift): repeated (done at least twice) shifting of the weight between the cow’s two back hooves, done by lifting each hoof off the ground before landing it in the same location. 4. Uneven bearing of weight during movement (Uneven): the cow places weight unevenly between her right and left hooves when being moved from side to side. A cow was considered lame when 2 or more of the four behaviours were present. Inter- (across all behaviours, K = 0.86) and intra-observer repeatability (across all behaviours, K = 0.78) was evaluated weekly.

3.3.5.5 Time spent eating and ruminating

The time spent performing nutrition-related behaviours, i.e. eating and ruminating, was monitored on 12 of the 24 cows enrolled, with 6 from each treatment group selected at random. The 12 cows were each fitted with an ear-mounted activity logger (CowManager SensOor, Agis Automatisering, Harmelen, The Netherlands), which was clipped on their identification tags. The use of the SensOor® device in tie-stall settings was validated in a study by Zambelis et al. (2019), which showed that combining the rumination and eating times calculated by the device into the "Eating/Rumination time" category yielded a reliable measure indicating the proportion of the time budget allocated to nutrition-related behaviours, i.e. eating and rumination: correlation between visual observation and data from the logger yielded a r = 0.83 for the combination of eating and rumination, compared to r = 0.27 for rumination alone and r = 0.69 for eating alone. Thus, the use of the SensOor® devices served to measure the percentage of time per hour cows from either treatment spent performing nutritional behaviours, and as a means of ensuring that neither treatment negatively impacted the cows' ability to eat and ruminate as needed.

3.3.6 Milk production and quality

Milk production and milk components were recorded for all cows enrolled in the trial. Production (in kg) was recorded at each milking by the DeLaval milking units, and automatically entered in DeLaval's DelPro™ software (v. 1.5; DeLaval, Tumba, Sweden), from where the data was extracted. The daily milk yields were then averaged weekly for all animals. In addition to that, milk samples were collected weekly from each cow, during the Thursday PM milking and the Friday AM milking, with milk from the two milkings mixed together in a 50:50 proportion to get a sample representative of one full day. These milk samples were sent off to Valacta (Ste-Anne-de-Bellevue, Quebec, Canada) for analysis of the milk components. From the Valacta report, Somatic cell count (SCC; '000 cells/mL) was converted to Somatic Cell Score using the formula detailed in Shook (1993).

3.4 Statistical analysis

Differences between chain length treatments and over time were analyzed in SAS 9.4 using a mixed model:

$Y_{ijkl} = \mu + trt_i + block_j + row_k + cow_{ijk} + week_l + (trt*week)_{il} + e_{ijkl}$

Where: Y_{ijkl} is the dependant variable; the outcome measure of the cow from the j^{th} block (parity and lactation stage) in the k^{th} row on the combination of the i^{th} chain length and the l^{th} week; trt_i is the fixed effect of the i^{th} chain length; $block_j$ is the fixed effect of the j^{th} parity and lactation stage combination; row_k is the random effect of the k^{th} row in the barn; cow_{ij} is the random effect of the cow from the j^{th} block on the i^{th} chain length and found in the k^{th} row; $week_l$ is the fixed effect of the l^{th} week; $(trt*week)_{il}$ is the fixed effect of the interaction, the specific effect of the combination of the i^{th} chain length and the l^{th} week; e_{ijkl} is the random residual associated with the outcome measure of the cow from the j^{th} block in the k^{th} row on the combination of the i^{th} chain length and the l^{th} week.

As our main interest was to compare the effects of our treatments in the short-term and in the long-term, measures of weeks 1-3 were grouped together as the "Short-term" time period, and the measures of weeks 8-10, as the "Long-term" time period. Week 6 data was added in as the "Mid-term" as an in-between time point. A Scheffé adjustment was employed to account for the multiple comparisons between the main effects of the time points, and a Dunnett adjustment was employed as well, to account for the multiple comparisons between the two treatments in the different time points selected. The adjusted P-values, designated as P_D and P_S, are presented as >0.05 if non-significant, and as ≤ 0.05 if significant, as per the level of detail available from the statistical analysis output. Repeated measures were accounted for in the statistical model employed, with the covariance structure (AR(1), CS or UN) adjusted to the best fit for each analyzed variable, as determined using the BIC fit statistics PROC UNIVARIATE and PROC MIXED procedures were used to test normality against the residuals of all variables.

3.5 Results

3.5.1 Quality of lying-down movements: duration of intention movements

Duration of intention movements before lying was shorter for long chain cows than for recommended length cows (- 3.2 s; $P = 0.05$;Table 3.5.1) and decreased in the long term for all treatments (- 3.6 s; $P \leq 0.05$). None of the other indicators of lying-down quality differed between treatments nor over time ($P > 0.05$). Prevalence of contacts with stall elements was of 70 %, across all treatments and weeks. Overall, between 23 and 38 % of lying-down movements were scored as abnormal.

None of the indicators of rising quality differed between treatments. Detailed results can be found in Supplementary Table 3.1.

Table 3.5.1. Indicators of lying quality (duration of intention movements before lying down, duration of lying motion, contact with stall elements, attempts, hind quarters shifting, slipping, overall abnormal lying) and lying side of long chain and recommended length cows (treatments), in the short-, mid- and long-term, and for all weeks (time periods)

	Time periods[1]		Treatments[2]			
			Recommended length		Long chain	
Term	Lsmean[3]	SE	LSmean	SE	LSmean	SE
Duration of intention movements before lying-down, s						
Short-term	16.9 [a]	0.81	18.4	1.14	15.4	1.14
Mid-term	14.1 [a,b]	1.01	14.8	1.43	13.4	1.43
Long-term	13.3 [b]	0.92	15.5	1.23	11.1	1.37
All weeks	15.3	0.72	16.9 [x]	1.01	13.7 [y]	1.03
Duration of lying motion, s						
Short-term	9.9	2.65	11.4	3.64	8.5	3.85
Mid-term	8.7	1.73	10.4	2.45	7.0	2.45
Long-term	6.8	0.26	7.0	0.36	6.7	0.38
All weeks	8.7	1.37	9.8	1.89	7.6	1.99
Contact with stall elements, %						
Short-term	70.7	5.19	66.2	7.32	75.3	7.35
Mid-term	68.8	5.92	68.1	8.38	69.4	8.38
Long-term	69.1	5.61	67.2	7.68	71.0	8.19
All weeks	69.9	4.87	66.9	6.85	72.9	6.92
Attempts of lying, nb/lying event						
Short-term	1.0	0.01	1.0	0.01	1.0	0.01
Mid-term	1.0	0.01	1.0	0.01	1.0	0.01
Long-term	1.0	0.01	1.0	0.01	1.0	0.01
All weeks	1.0	0.00	1.0	0.01	1.0	0.01
Hind quarters shifting, %						
Short-term	17.5	6.14	18.3	7.40	16.7	7.42
Mid-term	22.2	6.99	18.1	8.79	26.4	8.79
Long-term	22.9	6.47	24.6	7.73	21.2	8.19
All weeks	20.1	5.95	20.4	7.08	19.8	7.14
Slipping, %						
Short-term	9.8	5.96	12.5	8.40	7.0	8.19
Mid-term	13.9	8.34	25.0	11.80	2.8	11.57

Long-term	8.1	5.35	14.6	5.81	1.6	7.45
All weeks	9.9	5.91	15.3	8.36	4.5	8.17
Lying on left or right, %						
Short-term	51.0	4.60	51.1	4.92	50.9	4.93
Mid-term	49.3	4.85	48.6	5.38	50.0	5.38
Long-term	51.9	4.73	52.8	5.07	51.0	5.26
All weeks	51.0	4.50	51.3	4.73	50.7	4.75
Overall abnormal lying, %						
Short-term	24.7	5.41	26.2	7.63	23.2	7.67
Mid-term	32.6	6.66	37.5	9.42	27.8	9.42
Long-term	29.0	5.97	32.9	8.12	25.0	8.76
All weeks	27.4	5.07	30.3	7.12	24.6	7.21

[1]Periods means within a column with different superscript (a, b, c) differ ($P < 0.05$)
[2]Treatments means within a row with different superscript (x, y, z) differ ($P < 0.05$)
[3]Average across treatments

3.5.2 Lying time

Cows enrolled in the trial spent an average of 11.9 ± 0.27 h/d lying down, with an average number of 13 ± 1.0 bouts/day, with an average duration of 1.0 ± 0.09 h/bout. Neither total lying time ($P = 0.43$) = 0.43), number of lying bouts ($P = 0.70$) and duration of lying bouts ($P = 0.49$) differed between treatments (Supplementary Table 3.2).

3.5.3 Use of space by cows: space outside of stall perimeter

Time spent outside the stall perimeter in the manger area, as indicate by the time spent outside of the stall by the withers, was greater for long chain cows than for recommended length cows (11 ± 1.1 vs 7 ± 1.1 % of daily time; $P = 0.05$; Table 3.5.2), and increased between the short- and mid-term (+ 4 % of daily time; $P \leq 0.05$) as well as between the short- and long-term (+ 3 % of daily time; $P \leq 0.05$). Use of the space outside of stall perimeter at the back and on the sides, as indicated by the percentage of time each of the two hip points spent outside the stall, did not differ between treatments. Average distance outside of the stall in the manger area, as indicated by the measure of distance outside of stall perimeter for the withers, increased significantly between the short- and long-term (+ 0.9 cm; $P \leq 0.05$) for both treatments. None of the measures of distance outside stall perimeter differed between treatments. There were no differences between treatments in the use of space inside the stall perimeter.

Table 3.5.2. Use of space outside of stall perimeter (time outside stall and minimum, maximum and average distance outside of stall confines) for left hip, right hip, and withers body points by long chain and recommended length cows (treatments) in the short-mid- and long-term, and for all weeks (time periods)

	Time periods[1]		Treatments[2]			
			Recommended length		Long chain	
	Lsmean[3]	SE	LSmean	SE	LSmean	SE
Time spent in the rear part of the stall, %						
Short-term	1.8	0.22	2.1	0.31	1.4	0.31
Mid-term	2.0	0.32	2.3	0.45	1.6	0.45
Long-term	1.8	0.26	2.4	0.35	1.2	0.39
All weeks	1.8	0.20	2.3	0.27	1.4	0.28
Time spent outside of stall by left hip, %						
Short-term	10.2	1.80	12.1	2.40	8.3	2.40
Mid-term	11.4	1.87	14.6	2.51	8.1	2.51
Long-term	11.1	1.84	12.9	2.44	9.4	2.49
All weeks	10.7	1.76	12.8	2.34	8.6	2.35
Minimum distance outside of stall for left hip, cm						
Short-term	0.2	0.04	0.1	0.06	0.3	0.06
Mid-term	0.2	0.11	0.2	0.15	0.3	0.15
Long-term	0.3	0.18	0.5	0.25	0.1	0.26
All weeks	0.2	0.08	0.3	0.11	0.2	0.11
Maximum distance outstide of stall for left hip, cm						
Short-term	48.5	16.28	35.8	23.03	61.1	23.03
Mid-term	53.5	18.51	43.0	26.18	64.1	26.18
Long-term	51.9	17.18	43.6	24.25	60.2	24.35
All weeks	50.5	16.66	39.6	23.56	61.3	23.57
Average distance outside of stall for left hip, cm						
Short-term	13.4	1.91	10.8	2.71	15.9	2.71
Mid-term	13.2	1.63	9.9	2.30	16.6	2.30
Long-term	14.8	2.65	10.4	3.69	19.1	3.80
All weeks	13.8	2.06	10.5	2.91	17.1	2.92
Time spent outside of stall by right hip, %						
Short-term	5.0	2.01	4.9	2.13	5.0	2.13
Mid-term	4.7	2.06	4.3	2.22	5.0	2.22
Long-term	5.5	2.03	6.2	2.16	4.7	2.19
All weeks	5.1	1.99	5.3	2.10	4.9	2.10
Minimum distance outside of stall for right hip, cm						
Short-term	0.4	0.19	0.7	0.27	0.2	0.27
Mid-term	0.4	0.10	0.5	0.14	0.2	0.14
Long-term	0.4	0.06	0.4	0.08	0.5	0.09
All weeks	0.4	0.10	0.5	0.14	0.3	0.14

Maximum distance outside of stall for right hip, cm						
Short-term	28.4	7.79	22.0	11.02	34.8	11.08
Mid-term	38.4	13.17	26.7	18.63	50.2	18.78
Long-term	39.2	11.30	28.3	15.41	50.1	16.38
All weeks	33.7	9.27	24.9	13.03	42.5	13.21
Average distance outside of stall for right hip, cm						
Short-term	8.4	3.82	7.3	3.98	9.6	3.98
Mid-term	8.4	3.88	6.1	4.10	10.6	4.10
Long-term	10.1	3.85	7.5	4.03	12.7	4.07
All weeks	9.0	3.79	7.2	3.92	10.8	3.92
Time spent outside of stall by withers, %						
Short-term	7.4 [a]	0.86	6.9	1.21	8.0	1.21
Mid-term	11.2 [b]	0.94	8.7	1.33	13.7	1.33
Long-term	10.1 [b]	0.90	6.7	1.26	13.5	1.30
All weeks	9.0	0.81	7.1 [x]	1.14	10.8 [y]	1.15
Minimum distance outside of stall for withers, cm						
Short-term	0.1	0.02	0.1	0.02	0.1	0.02
Mid-term	0.1	0.02	0.1	0.03	0.1	0.03
Long-term	0.1	0.02	0.1	0.03	0.1	0.03
All weeks	0.1	0.01	0.1	0.02	0.1	0.02
Maximum distance outside of stall for withers, cm						
Short-term	12.8	0.98	12.2	1.39	13.3	1.39
Mid-term	16.0	1.74	11.9	2.45	20.0	2.45
Long-term	16.7	1.79	13.8	2.44	19.6	2.63
All weeks	14.6	1.13	12.7	1.58	16.5	1.61
Average distance outside of stall for withers, cm						
Short-term	4.7 [a]	0.25	4.5	0.35	4.8	0.35
Mid-term	5.4 [a,b]	0.31	4.3	0.44	6.4	0.44
Long-term	5.6 [b]	0.28	4.8	0.38	6.4	0.41
All weeks	5.1	0.22	4.6	0.31	5.6	0.31

[1]Periods means within a column with different superscript (a, b, c) differ ($P < 0.05$)
[2]Treatments means within a row with different superscript (x, y, z) differ ($P < 0.05$)
[3]Average across treatments

3.5.4 Stall and cow cleanliness, and bedding quantity

Stalls (≥ 88 % of stalls scored clean) and cows (100 % of cows scored clean for leg, ≥ 97% for flank, ≥ 90 % for udder) were and stayed very clean in both treatments during the trial. The proportion of deep-bedded stalls remained low (≤ 13 % of stalls scored deep-bedded) throughout the trial, with no difference between treatments ($P = 0.59$).

3.5.5 Total time spent eating/ruminating

Proportion of time allotted to eating and rumination behaviours averaged 41.10 ± 1.56 %/h and 45.58 ± 1.55 %/h for long chain and recommended chain lengths, respectively, with no difference between treatments ($P = 0.15$).

3.6 <u>Discussion</u>

3.6.1 Quality of lying-down and rising movements

The results of this trial show that duration of intention movements was shorter when cows were given longer chains than with the recommended length. Gustafson and Lund-Magnussen (1995) previously concluded that the shorter duration of the examining movements (with a definition equivalent to that of the Intention movements used in this trial) could be interpreted as a decrease in hesitation before lying-down. Intention movements are thus thought to be an indicator of ease of movement at lying down, in the specific context of tie-stalls and other cubicle systems. In this trial, the general housing conditions were identical for both treatment groups, with only the length of the chain varying, thus leading to the conclusion that the additional length of chain granted led to an improvement in the cows' ease of movement and confidence within their environment. While both groups improved over time, indicating adaptation to their new stalls akin to what was observed by St John (2019), the duration of intention movements was still 4.38 seconds, or 28% shorter for long chain cows, even in the long term, a further indication of the beneficial effect the added length had on cow ease of movement.

Previous studies comparing tie-stall-housed cows with or without access to exercise found that providing exercise reduced the time cows took to lie down (Herlin, 1990; Popescu et al., 2013) and reduced contacts with the stall elements (Popescu et al., 2013). The provision of exercise has been long since linked with improved health of the feet and legs, as it may be due to an improved endurance of leg muscles or to increased circulation of blood and other tissue fluids within the limbs and joints aiding in vigor as well as injury recovery (Gustafson and Lund-Magnussen, 1995). While we did observe an improved confidence as per the reduced intention movement phase in long chain cows, our treatments had no significant impact on contacts with the stall or the duration of the lying down movement itself, unlike what could be expected from cows benefiting from a better opportunity of movement. The fact that cows seemingly more at ease in their environment still hit on the bars during a high percentage (about 70%) of their lying down movements may indicate a problem with the positioning or with the design of the side dividers, which were the stall elements the cows hit most of the time. Similar results were observed by (St John, 2019), with a prevalence of contacts with environment as high as 80.6%.

3.6.2 Lying time

Contrary to what could be expected from cows better at ease in their environment, no significant differences were observed in the resting behaviours, especially the number of lying bouts per day. Chaplin and Munksgaard (2001) showed a link between the difficulties cows experienced to rise and the number of lying bouts per day, with cows experiencing more difficulties (i.e. less at ease) performing fewer rising and lying-down movements per day. These results also correspond to what is found in lame cows, which were found to have fewer lying bouts per day compared to healthy cows (Solano et al., 2016). The number of lying bouts per day did not significantly differ between the two treatments, in this study, and was similar to the averages found in other experiments (Chaplin and Munksgaard, 2001; Palacio, 2016; St John et al., 2018). One possible explanation for this observation is that other factors, such as the softness of the stall bed (Rushen et al., 2007), had a greater impact on the comfort of cows when they were lying down, and on their need to switch between postures. The quantity of bedding, also known to contribute to the comfort of the bed and concurrently impact the cow's lying time (Tucker et al., 2009), was low for both treatments, while unfortunately corresponding to the situation observed on commercial farms across Canada (Nash et al., 2016).

3.6.3 Use of space outside of stall confines

While no differences were observed between treatments, the percentage of time spent outside of the stall confines (all points confounded) increased over time. One part of this phenomenon can be attributed to the increase in chain length experienced by both treatment groups: the length of chains at the farm was on average 0.84 m, prior to the trial. While being longer than the Canadian average of 55 cm recorded by Bouffard et al. (2017), this chain length remains below the recommendation of 1.00 m that was implemented for the recommended length group. Thus, all cows had a chain longer than what they were previously used to, allowing them to increase their use of space by moving partly outside of their stall confines. These results indicate that cows from both treatment groups got used to their set-up and further tested its limits with time, and that the animals on trial did not immediately discover and fully use their new limits, showing that the changing of habits requires time. This effect may be further enhanced by the fact that no primiparous cows were included in this trial: all experimental cows had experienced at least one lactation of conditioning to their previous in-stall conditions. The percentage of time the withers were found outside of the stall parameters was higher in the long chain group, compared to the recommended length cows, and increased in the mid and long terms, compared to the short term, for both treatments. While this is another indication of how all cows gradually adapted to their new set-up, the difference between the two treatments shows how longer chains resulted in cows being more at ease in their environment, moving more as a result. In this case, however, cows seem to have increased their use of the front of the stall, contrary to what was expected. The main use of the stall front when standing is eating. Eating and rumination times, were not different between treatments, although numerically smaller in long chain cows compared to recommended length cows. This seems to indicate that the increased length enabled them to better reach their feed and to eat faster as a result. The proportions of time allotted to eating and rumination were also found to be smaller in this trial than in a previous tie-stall experiment (St John et al, 2018), a further indication of the beneficial impact of the increase in chain length all trial cows benefitted from in this case. A more detailed listing of the behaviour the cows conducted when expanding their use of space further in the stall front would yield more information, but unfortunately, was not part of the measures collected for this experiment. It is also interesting to mention that while cows used space further outside in the front of the stall, this difference was not reflected in the cleanliness levels of neither treatments. Much like what was found in a previous study by (St John et al., 2018) in a similar set-up, more than 90% of stalls and cows were found to be clean.

3.7 <u>Conclusion</u>

Our results show that increasing chain length further than what is currently recommended leads tie-stall-housed lactating dairy cows to modify the way they use the space available to them. Indeed, this modification seemingly improves their movement within the confines of the space accessible to them. Increasing chain length also improves cows' ease of transition between the standing and the recumbent postures, and appears to allow cows to better reach their feed. Therefore, increasing the length of the chain poses as a low-cost modification that could be implemented on tie-stall dairy farms as part of a series of measures aiming to improve dairy cow comfort at their stall. However, the high prevalence of contacts with the stall elements that were recorded in this trial, as well as the high prevalence of abnormal rising and lying-down movements seem to indicate that other stall parameters may play a role in hindering the cows' ability to move within her stall. While the modification to chain length allows cows to move more, it does not fully substitute in place of other housing systems and management practices in termes of increasing movement opportunity for dairy cows.

3.8 References

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3.9 Supplementary figures

Supplementary Table 3.1. Indicators of quality of rising movements (duration of rising movement, attempts, backward movement on carpal joints, contact with tie-rail, delayed rising, and overall abnormal rising) of recommended length and long chain cows (treatment) in the short-, mid-, and long-term, and for all weeks (time periods)

	Periods[1]		Treatments[2]			
			Recommended		Long chain	
	LSmean[3]	SE	Lsmean	SE	LSmean	SE
Duration of rising movement, s						
Short-term	10.0	2.02	8.0	2.86	12.1	2.87
Mid-term	10.8	3.34	7.3	4.72	14.3	4.75
Long-term	11.9	3.53	9.2	4.98	14.7	5.03
All weeks	10.8	2.72	8.3	3.84	13.3	3.86
Attempts of rising, number/rising movement						
Short-term	1.1	0.20	1.0	0.29	1.2	0.29
Mid-term	1.2	0.22	1.0	0.31	1.3	0.31
Long-term	1.4	0.21	1.5	0.30	1.3	0.31
All weeks	1.2	0.19	1.2	0.27	1.3	0.27
Backward movement on carpal joints, %						
Short-term	21.3	7.45	17.6	10.52	25.0	10.54
Mid-term	27.8	7.91	27.8	11.19	27.8	11.19
Long-term	26.5	7.71	24.7	10.74	28.2	11.06
All weeks	24.1	7.26	21.7	10.25	26.5	10.29
Contact with tie-rail, %						
Short-term	5.8	2.07	6.5	2.91	5.1	2.94
Mid-term	6.3	2.97	8.3	4.20	4.2	4.20
Long-term	4.9	2.54	8.3	3.33	1.5	3.83
All weeks	5.6	1.72	7.4	2.39	3.7	2.48
Delayed rising, %						
Short-term	1.6	0.69	2.3	0.97	0.9	0.98
Mid-term	1.4	1.02	0.0	1.45	2.8	1.45
Long-term	1.2	0.84	1.4	1.11	0.9	1.27
All weeks	1.4	0.59	1.6	0.82	1.2	0.85
Overall abnormal rising movement, %						
Short-term	30.1	7.51	25.5	10.62	34.8	10.63
Mid-term	33.3	8.10	31.9	11.45	34.7	11.45
Long-term	30.0	7.78	31.1	10.84	28.9	11.17
All weeks	30.6	7.36	28.4	10.38	32.8	10.42

[1]Periods means within a column with different superscript (a, b, c) differ ($P < 0.05$)
[2]Treatments means within a row with different superscript (x, y, z) differ ($P < 0.05$)
[3]Average across treatments

Supplementary Table 3.2. Total lying time, number of lying bouts, and duration of lying bouts of recommended length and long chain cows (treatment) in the short-, mid-, and long-term, and for all weeks (time periods)

	Time periods[1]		Treatments[2]			
			Recommended length		Long chain	
	Lsmean[3]	SE	Lsmean	SE	LSmean	SE
Total lying time, h/d						
Short-term	12.1	0.29	11.9	0.41	12.4	0.41
Mid-term	11.9	0.33	11.6	0.46	12.1	0.47
Long-term	11.5	0.31	11.4	0.43	11.6	0.46
All weeks	11.9	0.27	11.7	0.38	12.1	0.38
Number of lying bouts, bouts/d						
Short-term	13.2	1.00	13.0	1.13	13.4	1.13
Mid-term	12.9	1.04	12.2	1.20	13.6	1.21
Long-term	12.9	1.03	13.0	1.16	12.9	1.20
All weeks	13.0	0.98	12.8	1.08	13.2	1.09
Duration of lying bouts, h/bout						
Short-term	1.0	0.09	1.0	0.10	1.0	0.10
Mid-term	1.0	0.10	1.1	0.11	1.0	0.11
Long-term	1.0	0.09	1.0	0.11	1.0	0.11
All weeks	1.0	0.09	1.0	0.10	1.0	0.10

[1]Periods means within a column with different superscript (a, b, c) differ ($P < 0.05$)
[2]Treatments means within a row with different superscript (x, y, z) differ ($P < 0.05$)
[3]Average across treatments

Supplementary Table 3.3. Stall cleanliness, bedding quantity and cow cleanliness (flank, udder and leg) for recommended length and long chain cows (treatment) in the short-, mid- and long-term, and for all weeks (time periods) results

	Time periods[1]		Treatments[2]			
			Recommended length		Long chain	
	Lsmean[3]	SE	LSmean	SE	LSmean	SE
Stall cleanliness, % stalls scored clean						
Short-term	92	3.8	89	5.3	94	5.3
Mid-term	96	5.5	100	7.8	92	7.8
Long-term	90	4.4	91	6.3	89	6.3
All weeks	92	2.3	91	3.2	93	3.2
Bedding quantity, % stalls scored deep-bedded						
Short-term	4	4.3	3	6.1	6	6.1
Mid-term	4	5.7	0	8.0	8	8.0
Long-term	10	4.5	8	6.4	13	6.4
All weeks	6	4.1	3	5.8	8	5.8
Flank cleanliness, % cows scored clean						
Short-term	99	1.1	100	1.5	97	1.5
Mid-term	100	1.9	100	2.6	100	2.6
Long-term	100	1.1	100	1.8	100	1.8
All weeks	99	0.6	100	0.8	98	0.8
Udder cleanliness, % cows scored clean						
Short-term	97	4.0	100	5.7	94	5.7
Mid-term	95	4.9	100	6.9	90	6.9
Long-term	94	4.0	100	5.9	92	5.9
All weeks	96	3.6	100	5.1	91	5.1
Leg cleanliness, % clean cows						
Did not converge; 100% of cows clean in all treatments and time periods						

[1]Periods means within a column with different superscript (a, b, c) differ ($P < 0.05$)
[2]Treatments means within a row with different superscript (x, y, z) differ ($P < 0.05$)
[3]Average across treatments

Supplementary Table 3.4. Portrait of the sample of cows used in the chain length trial for common outcome measures of welfare (Body Condition Score, Lameness, Cleanliness, Body Injuries) and mill production and quality

	Baseline		Short-term		Mid-term		Long-term	
Outcome measure	Recom mended	Long chain	Recom mended	Long chain	Recom mended	Long chain	Recom mended	Long chain
Body Condition score, average score	2.63	2.54	2.60	2.54	2.65	2.55	2.60	2.49
Lameness, % cows scored lame	58	42	50	36	50	36	28	44
Cleanliness of cows								
Leg, % cows scored dirty	0	0	0	0	0	0	0	0
Flank, % cows scored dirty	0	0	0	3	0	0	0	0
Udder, % cows scored dirty	0	0	0	6	0	9	0	8
Body injuries, % cows injured[1]								
Shoulder	0	0	6	13	0	5	1	2
Flank	0	0	1	8	4	9	0	6
Back	0	4	1	4	0	9	0	0
Hip bone	0	0	6	1	0	5	0	0
Sacrum	0	0	0	1	0	0	1	0
Pin bone	0	0	0	0	0	0	0	0
Hind leg	8	8	11	14	4	14	4	12
Anatomical knee	33	38	29	43	38	41	30	30
Lateral calcaneus (hock)	50	46	69	85	58	91	76	82
Dorsal calcaneus (hock)	0	0	4	10	13	23	20	28
Medial calcaneus (hock)	0	0	0	3	0	9	0	10
Lateral tarsus (hock)	79	71	83	75	88	95	97	72
Medial tarsus (hock)	0	0	3	0	8	0	6	0
Carpal joints (knees)	50	25	74	60	58	45	46	51
Distal neck	0	0	0	0	0	0	0	0
Medial neck	0	8	22	0	8	0	3	4
Proximal neck	25	8	14	3	17	9	9	8
Milk production (kg/d)	44.4	46.7	43.7	44.9	42.1	42.0	40.8	39.4
% cows with somatic cell count > 200 000 cells/mL	0	8	3	8	0	10	3	11
Somatic cell score, average score	0.92	1.12	1.08	1.25	1.23	1.54	1.36	1.74

[1] % cows with scores 2, 3, and 4 for a given location

CHAPTER 4 – WOULD COWS BENEFIT FROM "KING-SIZE" BEDS? IMPACT OF DOUBLING STALL WIDTH ON THE RESTING COMFORT OF LACTATING DAIRY COWS HOUSED IN TIE-STALLS

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4.1 Abstract

Tie-stall dairy cows spend their whole days in the same space, which, therefore, must be designed to accommodate all the activities they conduct. Lying is a very important behaviour for dairy cows and a critical response variable for assessing stall designs, to ensure that their needs for resting space are met. The objective of this study was to determine if increasing tie-stall width alters the lying behaviour of lactating dairy cows. Two treatments were compared: the current recommendation (139 cm) and a double stall (284 cm). 16 cows were blocked by parity and lactation stage, then randomly allocated to a treatment and a stall within one of two rows in the barn, for a period of 6 weeks. Stall length was of 188 cm. Leg-mounted accelerometers were used to record lying behaviours. Cows were recorded on video 24h/wk, using surveillance cameras positioned above the stalls. Video data from weeks 1, 3 and 6 were recorded at a rate of 1 frame per minute, and analyzed by a trained observer to assess the position and the location of the cows' body, head, and limbs during the lying hours. Lying behaviours, and frequency of each position and location were analyzed in SAS using a mixed model in which treatment, block and week were included as fixed factors, and cow and row, as random factors. Multiple comparisons were adjusted for using the Scheffé method. Results indicate that cows in the double stalls fully extended their hindlimbs more often than the control cows (21.7 % vs 7.64 %, P = 0.015). They also intruded in the neighboring stalls with their hindlimbs less often than the control cows (1.3 vs 14.7 %, SE = 0.59; $P < 0.001$), instead positioning them inside their own stall more often (92.7 vs 84.6 %, SE = 1.32 %; $P < 0.001$). Use of the second stall in the double stall group totaled 11.6 ± 3.06 %, 5.1 ± 2.42 %, 33.8 ± 6.45 %, and 18.0 ± 5.36 % respectively for the head, front legs, hind legs, and body. Total lying time did not differ (P = 0.24) between the double stall group (716.1 ± 25.04 min/d) and the single stall group (670.8 ± 24.98 min/d). Contacts with stall hardware during lying-down movements were also less frequent in double stalls (43.1 % vs 77.1 %, SE = 8.16 %; $P = 0.01$). These results suggest that dairy cows housed in double stalls modified their resting habits and use of space in a way similar to cows housed in stall-free systems and on pasture. Increasing stall width beyond the current recommendation is likely to benefit the cows by improving their ability to rest.

4.2 Introduction

Stall width can be defined as the distance between the centers of the two dividers which work as the right and left side limits of each individual stall. It is a design feature common to all cubicle housing systems, tie-stall and free-stall alike. In both tie-stall and free-stall systems, the cubicle or the stall is the designated area for the cow to lie down and rest, although it is also used by animals for standing (Tucker et al., 2009). The width of the stall defines the lateral space made available to the cow for standing, lying, and for her lying-down and rising movements, while the structures defining the stall and its width are meant to work as limits guiding the cow's position within the stall. Therefore, stall width must accommodate for the cow's space requirements for resting, as well as for during the transition movements between her standing and recumbent postures. Current data collected from the dairy industry all around the world shows a low compliance to stall width recommendations, both in tie-stall (Bouffard et al., 2017; Jewell et al., 2019a) and free-stall systems (Plesch, 2011; Barrientos et al., 2013; Chapinal et al., 2013, 2014; Jewell et al., 2019a). Compliance to stall width recommendation has been associated with reduced risks for a few common outcome measures of cow welfare, namely neck injuries and lameness (Bouffard et al., 2017), which, along with hock injuries and knee injuries, were found to be highly common on commercial farms nowadays (Zaffino Heyerhoff et al., 2014; Nash et al., 2016; Bouffard et al., 2017). Another phenomenon found to be common in stall systems are the contact with the dividers and other stall elements during lying-down and rising events (Plesch, 2011; Popescu et al., 2013; St John, 2019; Palacio et al, *in prep*). While a restrictive neck rail placement has been cited as hindering the capacity of free-stall cows to use the stalls for standing (Bernardi et al., 2009), the role other stall-defining elements has not been thoroughly studied. Yet, given the high frequency of contacts between cows and the stall side dividers, there are reasons to believe that these pieces of stall hardware may restrict the capacity of the cows to use the stall for resting, and to properly and comfortably transition towards the recumbent posture, especially if they result in injuries. Data from previous studies has found that even injuries which are classified as "mild" may be of significance for the welfare of dairy cows (Haager, 2016), reinforcing the importance of preventing such contacts as their impact on the cows' welfare may be more considerable than it appears. Furthermore, cows in stall-free systems such as pastures and loose-pens were found to exhibit different resting postures, namely fewer narrow postures, than stall-housed animals (Shepley et al., 2019; van Erp-van der Kooij et al., 2019). Conversely, cows housed in an undercrowded cubicle house were found to lie in smaller groups and to extend their hind legs more than cows housed in a cubicle house containing 1 stall per animal (Wierenga et al., 1985). This evidence seems to point towards a form of restriction in the resting capacity of dairy cows imposed either by the stalls themselves, by the presence of conspecifics in close proximity, or a combination of those factors. To evaluate whether or not the benefits of stall-free systems can be obtained with stalls much larger than the current recommendation, we have conducted a controlled-design trial evaluating the behaviour and the welfare of tie-stall-housed dairy cows fitted either with a stall of the current recommendation or one of double width. We hypothesized that with a greater amount of lateral space, dairy cows would modify their lying postures and their use of the space to better exploit the additional area granted to them, enabling them a better quality of rest with fewer disturbances from neighboring cows.

4.3 <u>Materials and Methods</u>

4.3.1 Ethics Statement

The certified Animal Care Committee of McGill University and affiliated hospitals and research institutes reviewed and approved the use of animals in this project and all procedures (#2016–7794). All aspects of this study meet the high standards established by the Canadian Council on Animal Care to ensure the continued humane and ethical use of animals in research.

4.3.2 Cows and treatments

The trial took place at the Macdonald Campus Dairy Complex, from June 5th, 2017 to August 14th, 2017 (6 weeks of data collection). The 16 cows enrolled were blocked in 8 pairs according to parity and stage of lactation. There were 2 parity 1, 7 parity 2, 4 parity 3, and 3 cows at parity 4 or more. Cows were in the early (4) and mid (12) lactation, with the enrolled animals averaging 157 DIM and 2.51 for Body Condition Score. The cows were assigned to and housed for 6 weeks into either a single stall (hereafter, **single**) meeting the current recommendation for width, i.e. [2x(width of the cow at the hips) + 5 cm] (National Farm Animal Care Council and Dairy Farmers of Canada, 2009; Anderson, 2014; Valacta, 2014), or into a double stall (hereafter, **double**). Average stall widths were 139 cm for Single, and 284 cm for Double. To create each double stall, the central divider between two cubicles was removed, and no cow was put in the second cubicle. The tie-chain attaches were left in their original positions on the tie-rail, such that double-width treatment cows were tied in either the right or the left portion of the stall. The side was drawn at random. Cow body dimensions were measured prior to the beginning of the trial. Average height at rump was of 152.17±2.85 cm, and average width at hips was of 65.87±4.70 cm.

4.3.3 Housing and management

Experimental cows were housed in two rows, both facing a wall in the Macdonald Campus Dairy Complex barn. Cows were housed in a stall that was at ±5 cm of the current recommendations for length (National Farm Animal Care Council and Dairy Farmers of Canada, 2009; Anderson, 2014; Valacta, 2014), according to their individual body dimensions. Average stall length was of 188.3 cm. For all stalls, the tie-rail position met current recommendations (National Farm Animal Care Council and Dairy Farmers of Canada, 2009; Anderson, 2014; Valacta, 2014), i.e., at a height of 48 inches from the stall base, and a forward position of 14 inches from the manger wall. Chain length was of 1.00m for all stalls. All the gutters in the barn were covered with a grid. The stall base consisted in KKM longline rubber mats (Gummiwerk Kraiburg Elastik GmbH & Co. KG, Tittmoning, Germany) on which a fine layer of sawdust bedding (about 2 cm) was added once per day, in the morning. More bedding was added in the evening, for the cows that were considered as needing it by the barn staff. Management of the cows in the trial followed barn routine: cleaning of the stalls and the gutters was done as needed by the barn staff, between 5:00 and 21:00. Cows were milked in their stall twice daily, between 5:00 to 7:00, and 17:00 to 19:00. The herd was fed 4 times daily: one full ration was served in the morning (6:00), with a top-up served later in the morning. A second serving of ration was delivered in the afternoon (16:00), and the last batch was served in the evening. Cows were fed a TMR consisting of grass and legume silage, corn silage, dry corn, high moisture corn, and protein and mineral supplements. Feed was pushed back 6 times per day by the farm staff. Water was available ad libitum from self-serving water bowls shared between adjacent stalls (1 bowl per 2 cows).

4.3.4 Video Recording

Each cow was filmed 24h per week, using StereoPlus surveillance cameras (Smart Turret 2.8, Hikvision Digital Technology Co., Ltd., Hangzhou, China) installed above the tie-stalls, at a height of 338 cm off the stall surface. Each cow was filmed for a period of 24h on the same day every week, with the camera placed in the same position. The observation videos were used to evaluate the cows' lying postures and occupation of space during resting hours, as well as the quality of the lying and of the rising movements of the cows.

4.3.5 Measures

4.3.5.1 Quality of lying-down and rising movements

Evaluation of the quality of rising and lying-down movements was done through a visual assessment of the observation videos by one trained observer. The visual evaluation aimed to identify possible issues occurring during the rising and/or lying-down events. The observer scored

6 lying and 6 rising events per 24h per cow, distributed as 4 events selected at random during the day and 2 events randomly picked during the night hours, as this scheme was determined to be representative of a cow's lying and rising behaviour for a full day and a full week by the means of a validation study done during the development of the scoring method (Zambelis et al, *in review*). For the evaluation of the lying-down movements, the observer was looking at eight specific behavioural indicators (Table 4.3.1) : duration of the intention movements prior to lying down (s), duration of the lying down movement (s), number of lying attempts (#), contact with the stall elements (i.e. bars; %), slipping of the legs during the movement (%),shifting of the hind quarters during the event (%), lying down following an abnormal sequence ("dog sitting"; %), and lying on the right or the left side (%). A lying down event was considered abnormal whenever one or more of the following abnormal behaviour occurred: multiple (>1) attempts of lying, contact with the stall elements, slipping of the legs, stepping with the hind legs, abnormal lying-down sequence. For the evaluation of the rising movements, the observer was looking at six specific behavioural indicators (Table 4.3.2): the duration of the rising movement (s), contact with the stall elements (i.e. bars; %), shuffling back on the knees (%), delayed rising (%), number of rising attempts (#) , and rising following an abnormal sequence (called "horse rising"; %). A seventh category, termed overall abnormal rising (%) characterized the proportion of rising events in which one or more abnormal behaviour among the following occurred: contact with stall elements, shuffling back on the knees, delayed rising, presence of multiple (>1) attempts of rising, and abnormal rising sequence. One observer was responsible for all the scoring for both the quality of lying-down and the quality of rising movements. Regularly-conducted repeatability evaluations yielded kappa scores of 0.94 for both rising and lying evaluations, in comparison to the gold standard for the method. The intra-observer kappas were of 0.93 and 0.91 for lying and rising, respectively.

Table 4.3.1. Description of the lying-down behaviours and sampling units that were evaluated for all cows in all treatment groups[1]

Behaviour	Sampling Unit	Description of Behaviour
Duration of intention movements before lying down (phase 1)	Seconds	Length of time the cow repeatedly and continuously sniffs the lying surface with possible sweeping movements of the head without lying down Start of movement: when sniffing starts End of movement: when phase 2 begins
Duration of lying motion (phase 2)	Seconds	Length of time required to complete the lying motion Start of motion: the cow descends to one of the forelegs End of motion: the whole body touches the ground; body is stable
Contact with environment	Yes (1) or no (0)	Cow comes into contact with dividers and/or tie-rail during the lying motion.
Attempts of lying	Number of attempts	The number of attempts required to successfully complete the lying motion Failed lying attempt: Cow stands up after the start of a lying down motion (goes on one or both carpal joints and then back up onto hooves)
Hind quarters shifting	Yes (1) or no (0)	When on carpal joints, cow does multiple shifting motions with its hind quarters before lying down completely (≥ 3 sec)
Dog-sitting	Yes (1) or no (0)	Cow lies down with hind quarters first and then goes down on carpal joint
Lying on left or right	Left (1) or Right (0)	Direction the hind legs point when cow is lying (based on technician viewing cow from above)
Overall Abnormal Lying	Yes (1) or no (0)	Cow requires > 1 attempt to lie down and/or is scored as 'Yes' for contact with the tie-rail, hind quarter stepping, and/or dog-sitting

[1]Based on Zambelis et al (*in review*)

Table 4.3.2. Description of the rising behaviours and sampling units that were evaluated for all cows in all treatment groups[1]

Behaviour	Sampling Unit	Description of Behaviour
Duration of rising motion	Seconds	Length of time required to complete the rising motion Start of motion: cow is in sternal position, situated to propel itself forward End of motion: cow gathers its forelimb side by side on the stall bed.
Contact with tie-rail	Yes (1) or no (0)	While cow propels itself forward (with both carpal joints on the ground), its head or neck touches the tie-rail.
Backward movement on carpal joints	Yes (1) or no (0)	When resting on carpal joints, cow moves its front leg(s) backwards before or after propelling itself
Delayed rising	Yes (1) or no (0)	Cow rests on carpal joints for > 10 s
Attempts of rising	Number of attempts	The number of attempts required to successfully complete the rising motion Failed lying attempt: Cow propels itself forward from sternal position without successfully rising; can appear as a forward and back motion
Horse rising	Yes (1) or no (0)	Cow gets up first with front legs, then with hind legs
Overall abnormal rising	Yes (1) or no (0)	Cow requires > 1 attempt to rise and/or is scored as 'Yes' for contact with environment, backward movement on carpal joints, delayed rising, and/or horse rising

[1]Based on Zambelis et al (*in review*).

4.3.5.2 Postures and position in space of head, body and limbs during lying hours

The observation videos from weeks 1, 3 and 6 were used to assess of the postures and the position in space of the cows' body parts during resting hours. Images were extracted from these videos at a rate of 1 picture per minute of video, and only the images on which the cows were lying down were kept for the assessment. Pictures were visually assessed by one trained observer who characterized the posture of each limb, of the head, and of the body, using an ethogram adapted from Haley et al (2001;Table 4.3.3). The observer also noted the position of each body part in the space (Figure 4.3.1), either inside the stall (between the two dividers; TS), in either one of the neighboring stalls (NST), in the manger area (Ma), on the divider, or in the gutter area (Ga). For the Double Stall cows, the stall was further divided in two parts being the first and second half of the double stall, termed 'single stall' (i.e., the half of the stall on which the cow is tied) and 'second stall', to better characterize the use of the double stall by the animals. The frequency of use of each posture and location during resting time by each body part was computed (right and left sides combined, for the legs). Intra-observer repeatability for the single observer (the goldstandard) who evaluated all the sequences was 0.87 for the evaluation of lying postures, and 0.88 for the occupation of space.

Table 4.3.3. Detailed options for lying postures, for each of the body parts assessed visually on the images

Body part	Posture option	Details
Body	Lying on sternum	The body is resting on the ground[1]
	Lying on side	The body is resting flat on one side, with the legs of the supported underside extended and the head resting on the ground[1]
	Lying on right side or left side	The side on which the cow is resting; either her left or her right flank is against the ground
Head	Upright	The head is raised off the ground[1]
	Back	The head is positioned toward the posterior of the cow, resting against the body[1]
	Ground	The head is stretched and resting on the floor[1]
Front leg (right or left)	Tucked	Front leg is held under or at the side of the body, with a full plantar-flexion at the humoral joint[1]
	Extended	Front leg is extended in front of or to the side of the body[1]
Hind leg (right or left)	Tucked	Hind leg is positioned at an angle of fewer than 45 degrees in relation to the body axis, or underneath the body[1]
	Mid-position	Hind leg is positioned at an angle between 45 and 90 degrees in relation to the body axis[1]
	Extended	Hind leg is positioned at an angle of 90 degrees or greater in relation to the body axis[1]

[1] Based on Haley et al (2000, 2001)

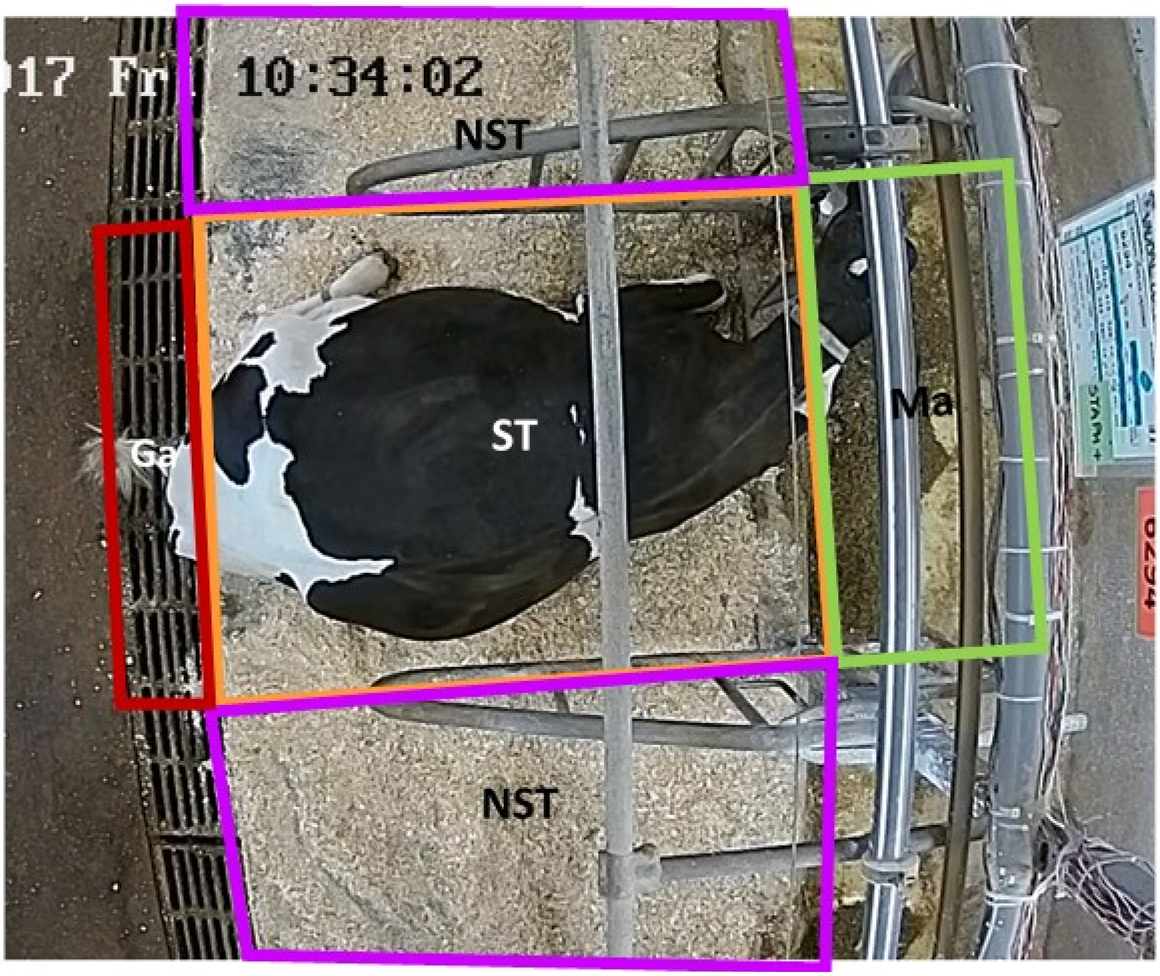

Figure 4.3.1. The different zones defined for the assessment of the position in space of the cows' body parts during lying time: stall (ST), neighbouring stall (NST), manger area (Ma), and gutter area (Ga)

4.3.5.3 Lying time

Lying time was automatically recorded by the means of leg-mounted data loggers (HOBO Pendant G Acceleration Data Loggers, Onset Computer Corporation, Pocasset, MA, USA) previously validated for use in tie-stall settings (Vasseur et al., 2012). The data loggers were secured on the hind leg of each cow using auto-adhesive flexible wrapping bandage (Vet-Wrap, CoFlex®Vet, Andover HealthCare inc, Salisbury, MA, USA) following Vasseur et al. (2012), and were switched weekly from side to side to avoid injury. Total lying time in hours per day, average number of lying bouts per day, and average duration of lying bouts, in hours/bout, were computed from the HOBO data using Excel macros (Microsoft Corp., Redmond, WA) for each week.

4.3.5.4 Clinical signs and cleanliness

Two trained observers conducted a visual assessment of injuries on seventeen different locations found on the cow's body, neck, front legs, and back legs, on both sides. The method, adapted from methodologies described in Gibbons et al (2012) and in Brenninkmeyer et al (2016), consisted in a detailed recording of the injury types (nothing, broken hair, bald spot, white scab, red scab, open wound, minor swelling, medium swelling, major swelling) present on each of the locations. The detailed injury types were then categorized on a scale of 0 to 4 according to the degree of severity, 0 = No injury, or nothing, and 4 = Open wound and/or Major swelling present. When more than one type of lesion was present, the most severe lesion or swelling score for the area was retained as the final score for the area. For analysis of injury scores, the score differences from the baseline (week 0) were used as the outcome measures, because initial state of injury of animals when they were enrolled in the trial could not be accounted for in the experimental design (i.e., cow selection). Inter-observer (overall average K = 0.79, across all locations) and intra-observer (overall average K = 0.85, across all locations) repeatability assessments were conducted on weeks 1 and 6.

Lameness was assessed once weekly by two observers, using video recordings and following Stall Lameness Scoring (SLS) methods adapted from Leach et al (2009), and described in further detail in Palacio et al (2017) and Gibbons et al (2014). Each cow was filmed standing from 3 different positions for a minimum of 10 seconds per side. Following that, the cow was then encouraged to move from one side to the other a few times. For each video, the observers recorded whether each of the four following behaviours were present or absent: 1. Standing on the edge (Edge): the cow positions one hoof (or both hooves) at the edge of the stall surface. 2. Resting of one limb (Rest): the cow rests one foot while standing still, indicated by a partial or a complete lifting of the foot off the ground. 3. Weight shifting (Shift): repeated (done at least twice) shifting of the weight between the cow's two back hooves, done by lifting each hoof off the ground before landing it in the same location. 4. Uneven bearing of weight during movement (Uneven): the cow places weight unevenly between her right and left hooves when being moved from side to side. A cow was considered lame when 2 or more of the four behaviours were present. Inter- (across all behaviours, K = 0.85) and intra-observer repeatability (across all behaviours, K = 0.81) was evaluated weekly.

Body condition score, cow cleanliness, and stall cleanliness and bedding quantity were assessed following procedures found in Vasseur et al (2013, 2015) and found on the Dairy Research Portal (https://www.dairyresearch.ca/cow-comfort.php#self).

Each cow's body condition score was assessed live by the same trained observer once per week except on week 5, using a 5-point scale system with increments of 0.25, where a cow that was scored at 2 or below was considered as severely underconditioned, and a cow that was scored above 2, as adequately conditioned. Intra- (overall average $K_w = 0.91$) and inter-observer (overall average $K_w = 0.65$) repeatability was evaluated at the beginning and at the end of the 6-week period.

The cleanliness of the lower leg, flank and lower udder regions were visually assessed once per week by one trained observer. Each area was scored on a scale of 0-3 and categorized as clean (scores 0-1) or dirty (scores 2-3). The proportion of cows with clean legs, clean flanks, and clean lower udder region in each treatment group was calculated each week. Inter-observer (overall average $K_w = 0.56$; 92% agreement between observers) and intra-observer (overall average $K_w = 0.79$; 95% agreement between observers) repeatability was assessed at the beginning, in the middle and at the end of the 6-week period.

The cleanliness of stalls and the quantity of bedding in the stalls was assessed twice per week, Thursday afternoon at 4:30, and Friday morning, at 4:30, to evaluate the stalls before they got cleaned by the farm staff. The cleanliness of each stall was scored on a scale of 0-4 and classified as clean (scores 0-1) or dirty (scores 2-4), and the depth of bedding of each stall was assessed, with a layer of bedding of 2 cm or thinner being scored as "little" (L), and more than 2 cm as "deep" (D). The two measures collected for each stall were used to calculate the proportion of clean stalls per treatment for each week, as well as the proportion of stalls with deep bedding per treatment for each week.

4.3.5.5 Time spent eating and ruminating

The time spent performing nutrition-related behaviours, i.e. eating and ruminating, was monitored on 12 of the 16 cows enrolled, with 6 from each treatment group selected at random. The 12 cows were each fitted with an ear-mounted activity logger (CowManager SensOor, Agis Automatisering, Harmelen, The Netherlands), which was clipped on their identification tags. The use of the SensOor® device in tie-stall settings was validated in a study by Zambelis et al. (2019), which showed that combining the rumination and eating times calculated by the device into the

"Eating/Rumination time" category yielded a reliable measure indicating the proportion of the time budget allocated to nutrition-related behaviours, i.e. eating and rumination: correlation between visual observation and data from the logger yielded a $r = 0.83$ for the combination of eating and rumination, compared to $r = 0.27$ for rumination alone and $r = 0.69$ for eating alone. Thus, the use of the SensOor® devices served to measure the percentage of time per hour cows from either treatment spent performing nutritional behaviours, and as a means of ensuring that neither treatment negatively impacted the cows' ability to eat and ruminate as needed.

4.3.6 Milk production and quality

Milk production and milk components were recorded for all cows enrolled in the trial. Production (in kg) was recorded at each milking by the DeLaval milking units, and automatically entered in DeLaval's DelPro™ software (v. 1.5; DeLaval, Tumba, Sweden), from where the data was extracted. The daily milk yields were then averaged weekly for all animals. In addition to that, milk samples were collected weekly from each cow, during the Thursday PM milking and the Friday AM milking, with milk from the two milkings mixed together in a 50:50 proportion to get a sample representative of one full day. These milk samples were sent off to Valacta (Ste-Anne-de-Bellevue, Quebec, Canada) for analysis of the milk components. From the Valacta report, Somatic cell count (SCC; '000 cells/mL) was converted to Somatic Cell Score using the formula detailed in Shook (1993).

4.4 Statistical analysis

Differences between stall width treatments and over time were analyzed in SAS 9.4 using a mixed model:

$$Y_{ijkl} = \mu + trt_i + block_j + row_k + cow_{ijk} + week_l + (trt*week)_{il} + e_{ijkl}$$

Where: Y_{ijkl} is the dependant variable; the outcome measure of the cow from the j^{th} block (parity and lactation stage) in the k^{th} row on the combination of the i^{th} stall width and the l^{th} week; trt_i is the fixed effect of the i^{th} stall width; $block_j$ is the fixed effect of the j^{th} parity and lactation stage combination; row_k is the random effect of the k^{th} row in the barn; cow_{ij} is the random effect of the cow from the j^{th} block on the i^{th} stall width and found in the k^{th} row; $week_l$ is the fixed effect of the l^{th} week; $(trt*week)_{il}$ is the fixed effect of the interaction, the specific effect of the combination of the i^{th} stall width and the l^{th} week; e_{ijkl} is the random residual associated with the outcome measure of the cow from the j^{th} block in the k^{th} row on the combination of the i^{th} stall width and the l^{th} week.

As our main interest was to compare the effects of our treatments in the short-term and in the long-term, we picked time points of interest, weeks 1 and 6, which are later referred to as the "Short-term" and "Long-term" time periods. Week 3 data was added in as the "Mid-term" to serve as an in-between time point. A Scheffé adjustment was employed to adjust for the issue of multiple comparisons. Repeated measures were accounted for in the statistical model employed, with the covariance structure (AR(1), CS or UN) adjusted to the best fit for each analyzed variable, as determined using the BIC fit statistics. PROC UNIVARIATE and PROC MIXED procedures were used to test normality against the residuals of all variables.

4.5 <u>Results</u>

4.5.1 Quality of lying-down movements: contact with stall elements

Proportion of contacts with stall elements during lying down was 34 % lower in **double** than in **single** stalls (Figure 4.5.1; $P = 0.01$). None of the other indicators of lying-down quality differed between treatments (Supplementary Table 4.1). Prevalence of overall abnormal lying-down movement decreased by 36 and 33 % between the short- and mid-terms ($P = 0.002$), and short- and long-terms ($P = 0.02$), respectively. None of the rising quality indicators differed between treatments (Supplementary Table 4.2).

4.5.2 Resting behaviour: Head, body and legs postures and position in space

Cows in double stall extended their hind legs more than cows in single stalls (22 ± 3.2 vs 8 ± 3.2 % of resting time; $P = 0.02$;Table 4.5.1), and use of the tucked posture with hind legs

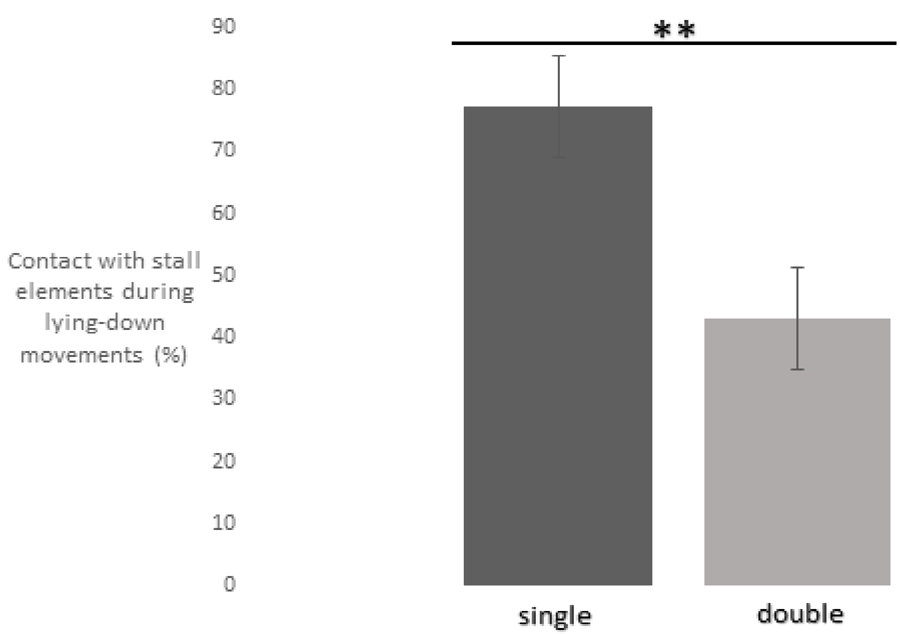

Figure 4.5.1. Prevalence of contacts with stall elements during lying-down movements for single and double stall cows for all weeks

increased between short- and long-term (+ 6 %; *P* = 0.04;Table 4.5.1). Postures of the front legs and of the head did not differ between treatments. Double stall cows tended to lie down more on their side than single stall cows did (+ 0.4 %; *P* = 0.09). Frequency of posture changes did not differ between treatments for any body part.

Table 4.5.1. Postures (tucked, mid, and extended) of hind legs during resting (% of resting time) for single and double stall cows (treatment) in the short-, mid-, and long-term, and for all weeks (time periods)

	Time periods[1]		Treatment[2]			
			Single		Double	
Posture	LSmean[3]	SE	LSmean	SE	LSmean	SE
Tucked, % of resting time						
Short-term	80.7 [a]	2.10	83.5	2.97	78.0	2.97
Mid-term	82.4 [a,b]	2.10	84.5	2.97	80.3	2.97
Long-term	86.8 [b]	2.10	90.8	2.97	82.9	2.97
All weeks	83.3	1.67	86.3	2.36	80.4	2.36
Mid, %						
Short-term	10.6	1.95	12.0	2.40	9.1	2.40
Mid-term	8.6	1.95	10.7	2.40	6.6	2.40
Long-term	8.0	1.95	6.9	2.40	9.1	2.40
All weeks	9.1	1.75	9.9	2.06	8.3	2.06
Extended, %						
Short-term	8.6	1.50	4.5	2.12	12.7	2.12
Mid-term	8.3	1.50	4.7	2.12	11.9	2.12
Long-term	5.1	1.50	2.3	2.12	7.9	2.12
All weeks	7.3	1.14	3.8 [x]	1.61	10.8 [y]	1.61

[1]Time periods means within a column with different superscript (a, b, c) differ ($P < 0.05$)
[2]Treatments LS-means and SE within a row with different superscript (x, y, z) differ ($P < 0.05$)
[3]Average across treatments

In terms of occupation of space during resting, cows in double stall had their hind legs more often inside their double stall than single stall cows (+ 8 % of resting time; *P* < 0.0001;Table 4.5.2), and less often in the stall of neighboring cows than cows in single stall (- 6 %; *P* < 0.0001). For both treatments, the use of the neighboring stall by hind legs slightly increased then decreased between terms. Double stall cows placed their head more often within their stalls (+ 25 %; *P* = 0.01;Table 4.5.3) and less often in the manger area (- 29 %; *P* = 0.008) than single stall cows. No difference between treatments was found for the occupation of space by front legs. Double stall cows utilized the free space of the second stall with hind legs (34 %), body (18 %), head (12 %) and front legs (5 %; Figure 4.5.2).

Table 4.5.2. Occupation of space (stall, neighboring stall, and gutter) by the hind legs during resting (% of resting time) for single and double stall cows (treatment) in the short-, mid- and long-term, and for all weeks (time periods)

	Time Periods[1]		Treatment[2]			
			Single		Double	
Area	LSmean[3]	SE	Lsmean	SE	LSmean	SE
Stall, % of resting time						
Short-term	88.4	2.08	84.1	2.61	92.7	2.61
Mid-term	86.2	2.08	82.0	2.61	90.5	2.61
Long-term	91.4	2.08	87.7	2.61	95.0	2.61
All weeks	88.7	1.33	84.6 [x]	1.32	92.7 [y]	1.32
Neighboring stall, % of resting time						
Short-term	8.3 [a,b]	0.78	15.1	1.11	1.6	1.11
Mid-term	9.7 [a]	0.78	17.6	1.11	1.9	1.11
Long-term	5.8 [b]	0.78	11.4	1.11	0.3	1.11
All weeks	8.0	0.42	14.7 [x]	0.59	1.3 [y]	0.59
Gutter, % of resting time						
Short-term	3.2	1.63	0.8	2.31	5.7	2.31
Mid-term	4.0	2.16	0.4	3.05	7.7	3.05
Long-term	2.8	0.70	0.9	1.00	4.6	1.00
All weeks	3.4	1.38	0.7	1.95	6.0	1.95

[1]Time periods means within a column with different superscript (a, b, c) differ ($P < 0.05$)
[2]Treatments means within a row with different superscript (x, y, z) differ ($P < 0.05$)
[3]Average across treatments

4.5.3 Lying time

Cows in double stalls had longer lying bouts (1.0 ± 0.05 vs 0.9 ± 0.05 h/bout; $P = 0.05$) and fewer lying bouts (12.1 ± 0.41 vs 13.5 ± 0.41 bouts/d; $P = 0.05$) than cows in single stalls. Total lying time did not differ between treatments, at 11.9 ± 0.42 h/d and 11.2 ± 0.42 h/d for double and single stall cows, respectively ($P = 0.24$).

Table 4.5.3. Occupation of space (divider, manger, stall, neighboring stall) by the head during resting (% of resting time) for single and double stall cows (treatment) in the short-, mid- and long-term, and for all weeks (time periods)

	Time periods[1]		Treatment[2]			
			Single		Double	
Area	LSmean[3]	SE	Lsmean	SE	LSmean	SE
Divider, % of resting time						
Short-term	0.0	0.01	0.0	0.01	0.0	0.01
Mid-term	0.0	0.01	0.0	0.01	0.0	0.01
Long-term	0.0	0.01	0.0	0.01	0.0	0.01
All weeks	0.0	0.01	0.0	0.01	0.0	0.01
Manger, % of resting time						
Short-term	58.5	4.79	70.9	6.77	46.2	6.77
Mid-term	54.0	4.79	67.9	6.77	40.1	6.77
Long-term	60.2	4.79	77.4	6.77	43.1	6.77
All weeks	57.6	3.96	72.1^{x}	5.60	43.1^{y}	5.60
Stall, % of resting time						
Short-term	35.6	4.37	25.2	5.92	46.1	5.92
Mid-term	39.0	4.37	27.9	5.92	50.0	5.92
Long-term	30.1	4.37	14.1	5.92	46.1	5.92
All weeks	34.9	3.67	22.4^{x}	4.89	47.4^{y}	4.89
Neighboring stall, % of resting time						
Short-term	5.8	3.56	3.9	4.43	7.7	4.43
Mid-term	7.0	3.56	4.2	4.43	9.8	4.43
Long-term	9.6	3.56	8.5	4.43	10.8	4.43
All weeks	7.5	2.91	5.5	3.34	9.4	3.34

[1]Weeks means within a column with different superscript (a, b, c) differ ($P < 0.05$)
[2]Treatments means within a row with different superscript (x, y, z) differ ($P < 0.05$)
[3]Average across treatments

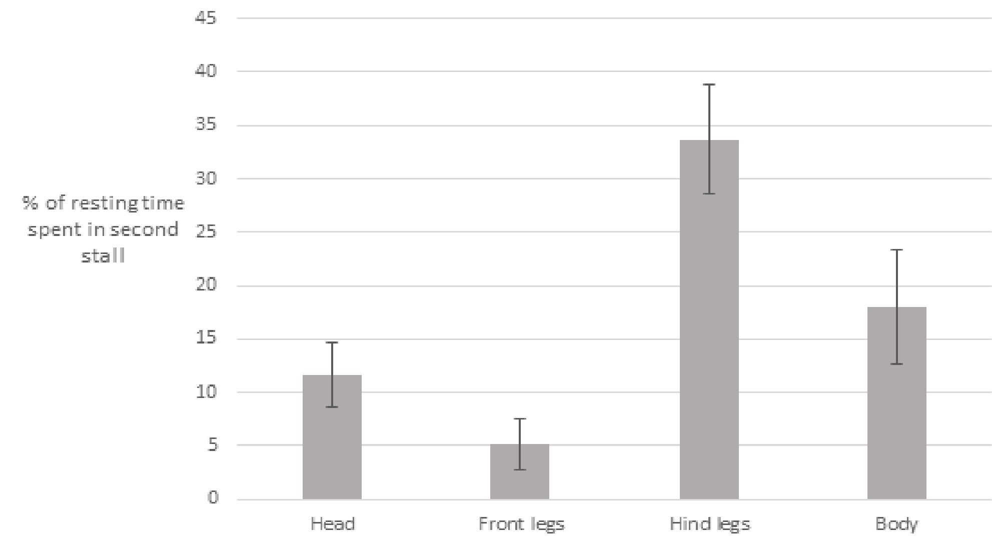

Figure 4.5.2. Use of free space of the second stall by double stall cows for each body part (head, front legs, hind legs, and body) during resting (% of resting time) for all weeks

4.5.4 Stall and cow cleanliness, and bedding quantity

Stalls (> 87 % of stall scored clean) and cows (> 87 % of cows scored clean for flank, > 95 % for leg, > 87 % for udder) were and stayed very clean in both treatments during the trial. Bedding stayed 2.3 times more in double than in single stalls (41.3 ± 3.35 vs 18.3 ± 3.35 % of stalls scored deep-bedded in double vs single stalls; *P* = 0.02).

4.6 Discussion

4.6.1 Quality of lying-down movements: contact with stall elements

Stall width had a significant impact on the occurrence of contacts with stall features during lying-down events. Such contacts decreased greatly (by 34 %) in double stalls compared to single stall. This shows that granting cows with more space allows them a greater margin for errors during transition movements, aiding with avoiding contacts with hardware, mostly dividers that is the stall elements cows hit the most. However, even in double stalls, contacts with the stall elements still occurred in about half of the lying-down events. This high prevalence is similar to that previously reported in tie-stall dairy cows (45 % of cows with no access to pasture have contacts with stall hardware during lying down (Popescu et al., 2013). To our knowledge, only one study evaluated the prevalence of such contacts during lying-down events in free-stall systems, to find levels comparable to those they observed in the tie-stalls: cows getting in contact with hardware in more than 50 % of lying-down events (Plesch, 2011).

The only studies reporting levels of contacts with stall hardware during lying-down movements below 25% are from animals housed in deep-bedded loose pens (10% of lying-down events with contacts in dry cows; Shepley et al., 2019) or from tie-stall cows previously granted access to pasture or outdoor exercise yards (21% of contacts with hardware during lying-down; Popescu et al., 2013). The trial we conducted previously (Chapter 3), evaluating the impact of a longer chain, also lead to the findings that an improved opportunity of movement aids in the ease of movement of dairy cows housed in tie-stalls, although we found no impact on the prevalence of contacts during lying down movements. Thus, the (lower) occurrence of contacts results from a variety of aspects, relating both to the cow herself and to her environment, with available space appearing alongside multiple other potential explanatory factors: movement opportunities (and their role on the cows' physical ability to move), bed comfort, and the state of cows themselves (lameness, injuries, stage of lactation) should all be considered for the cows' lying-down ability to be maximized.

4.6.2 Resting behaviours: lying postures, and occupation of space during resting time

The more frequent use of the extended posture with the hind legs in double stall cows, with nearly a three-fold increase in the proportion of time spent in that posture when resting, could be linked to the increase in the space available in double stall. While the studies that examined the postures used by cows when lying down are scarce, recent data from dry cows housed in deep-bedded loose pens providing more space per individual cow showed similar results: the loose pens cows used extended postures of the hind legs more frequently than did control cows housed in regular tie-stalls fitting the current recommendations (Shepley et al., 2019). Pasture cows were also found to use different lying postures than tie-stall-housed dairy cows, notably resting flat on their side more frequently (Krohn and Munksgaard, 1993). Our interpretation of the increase in the use of the extended posture of the hind legs is that dairy cows in stalls of the currently recommended width experience some form of restriction in their ability to expand their use of space when lying down, mainly due to the presence of cows in the nearby space of the neighboring stalls. When width was increased, cows no longer needed to accommodate as often with neighbors, and could extend their hind legs as often as desired, resulting in the increase that we observed. The decrease we observed in double stalls in the time spent intruding with the hind legs in the neighboring stalls seems to be a further indication that the current recommendation for stall width, although granting cows with more dynamic space than they require to transition between lying and standing (Ceballos et al., 2004), may in fact impose them some form of restriction when it comes to expressing certain lying postures. In other words, the current recommendation optimizes the dynamic space, but it seems like it does not the same for the resting space. In that sense, the current recommendations for stall width in tie-stall, and free-stall systems may limit greatly dairy cows with proper opportunities to express some of their natural resting behaviours. Extending of the legs further away from the body may also be linked with thermal regulation, with various postures being used by cows as a means of exposing more or less body surface to air for heat transfer (Tucker et al., 2007). Since our trial was conducted in the summer, there is a possibility that warmer weather resulted in a greater need for cows to expose more body surface and increase heat loss to their environment, the extended posture of the hind legs being one that could help filling that purpose. Therefore, as they favor resting while contributing to thermal comfort as well, resting postures serve a double purpose in this situation. This bides for further investigation of the potential benefits of improved opportunity to use extended leg lying postures, as thermal stress and its impacts on dairy cows and on farm profitability is an important challenge in dairy farming nowadays (Polsky and von Keyserlingk, 2017).

The main differences observed in the occupation of space when resting, such as the decreased time spent by the head in the manger area in double stall cows, with a concurrent increase in the use of the stall, are mostly linked to the way cows changed their ways of using the space allowed to them. The use of the second part of the double stall with the different body parts indicates that these cows, when granted with more room, lied down in different orientations compared to the one imposed to them – parallel to the dividers, and perpendicular to the manger wall – in single stalls. The fact that cows chose to lie down in a perpendicular orientation compared to the one they have to take in a regular stall may be linked to modification in the stall dimension proportions in double stall: their width (on average 284 cm) was greater their the length (on average 188 cm), contrary to the regular stall proportions, as per the current recommendations (National Farm Animal Care Council and Dairy Farmers of Canada, 2009; Anderson, 2014, 2016; Valacta, 2014). Dairy cows use more length than width in their environment, especially when they rise (Ceballos et al., 2004), and while the length of the stalls corresponded to current recommendations (National Farm Animal Care Council and Dairy Farmers of Canada, 2009; Anderson, 2014; Valacta, 2014), comparison with numbers found by Ceballos et al. (2004) shows that this length is insufficient. Thus, this response of cows may be a way to increase their comfort while resting and to reduce contacts with stall hardware during lying down movements, by swapping stall length and stall width so their stalls better fit their dynamic and resting space needs.

4.6.3 Lying time

Although total lying time did not differ between treatments (over 11 h per day), cows in double stalls had fewer (one less) and longer (10 min more) lying bouts than cows in single stalls. While overall, the number and duration of bouts remain comparable to what was found in other studies, both in tie-stall (Chaplin and Munksgaard, 2001; Palacio et al, in prep.; St John et al., 2018) and free-stall systems (von Keyserlingk et al., 2012; Westin et al., 2016; Solano et al., 2016), the difference between our treatments shows that the double stall is a better fit than the single stall for the cows' resting and dynamic space needs. Similar differences were found in terms of lying behaviour when comparing pasture environments to tie-stall systems (Krohn and Munksgaard, 1993) and free-stall systems (Olmos et al., 2009), a similarity that is likely due to some characteristics that our double stalls share with pasture systems: both offer a greater amount of space available per animal, increased possibility to lie further away from conspecifics, and decreased (or null) presence of stall hardware in close proximity to the cow. These characteristics altogether lead to a greater opportunity for cows to employ more various lying postures without hindrance from their environment, and without having to accommodate for the presence of the neighboring cows, improving overall bed comfort and allowing for better posture adjustment without the need for the cow to stand up and reposition herself in her environment.

4.6.4 Cow cleanliness, stall cleanliness, and quantity of bedding

In both treatments, cows (udder, leg, flank) and stalls were found to be clean over 85 % of the time in this trial, which contrasts with results by Ruud et al. (2011), who found that wider stalls were more likely to be soiled with manure transported by feet in free-stall, and by Bouffard et al. (2017), who found that wider stalls were associated with higher risks of cows having dirty legs and flanks. We scored the stalls before the milking hours, with the expectation that the stalls would be at their worst in terms of dirtiness in the morning, after nearly 8 hours without any personnel in the barn, yet did not detect any difference between treatments. Akin to common industry focus, a great attention is given, at the experimental farm, on the cleanliness of the cows and of the stalls, resulting in repeated cleaning rounds that occur during the day and which may have contributed to the results we obtained. The low percentage of dirty stalls and cows recorded in this trial seems to show that management practices aid in maintaining cleanliness, and the lack of difference between our treatments offers further support for the argument brought forward by (Bouffard et al., 2017), saying that the current prevalence of dirty animals does not justify disregarding cow comfort on the sole basis of maintaining cleanliness.

Increasing stall width seems to help in maintaining more bedding within the stalls. In this case, cow behaviour appears as the main potential explanatory factor, as double stalls allowed cows to expand their use of space by going in the second half of their cubicle instead of backing out of the stall and bring bedding along with their feet. Bedding is important for cow comfort (Tucker et al., 2009), and the current situation in the industry, i.e., a low proportion of sufficiently-bedded stalls (Nash et al., 2016) seems to indicate that keeping bedding in the stalls is a challenge on farms, as it was in this trial as well. Therefore, more research is needed to identify options that aid in maintaining suitable amounts of bedding in stalls at all times, including a potential further investigation of the impact of stall width on bedding.

4.7 Conclusion

Increasing the width of stalls beyond the current recommendation positively impacts the comfort and the resting capacity of lactating dairy cows: with an increased opportunity to express the lying postures they choose, double stall cows could more easily switch between postures and consequently slightly extend the duration of lying bouts before having to stand up. They could also more easily extend their hind legs without having to intrude in the neighboring cow’s stall, reducing the disturbances to the rest of their neighbors as well. Increasing stall width also reduced the prevalence of contacts with the stall elements during lying-down movements by a significant proportion, highlighting the need of dairy cows for a greater margin of error to perform lying-down movements in cubicle-based systems.

While increasing stall width had no impact on the cleanliness of the cows and of the stalls, it has helped in maintaining a greater amount of bedding within the stalls.

In the short term, providing a cow with a larger stall could serve as a punctual means of aiding a compromised animal’s recovery by aiding in its resting and in its ease during transitions. More data would be required, especially over time periods longer than 6 weeks, to investigate the impact such a modification to housing could have on the health and welfare of dairy cows in the long-term.

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4.9 Supplementary figures

Supplementary Table 4.1. Quality of the lying-down movements for single and double stall cows (treatment) in the short-, mid- and long-term, and for all weeks (time periods)

	Time periods[1]		Treatments[2]			
			Single		Double	
	LSmean[3]	SE	Lsmean	SE	LSmean	SE
Duration of intention movements prior to lying-down, s						
Short-term	18.6	20.21	17.9	24.13	19.4	24.13
Mid-term	39.4	20.21	16.9	24.13	61.9	24.13
Long-term	19.7	20.21	18.4	24.13	21.0	24.13
All weeks	25.9	18.15	17.7	20.59	34.1	20.59
Duration of lying-down motion, s						
Short-term	6.2	0.57	6.5	0.81	5.9	0.81
Mid-term	6.4	0.57	6.3	0.81	6.6	0.81
Long-term	5.3	0.57	5.4	0.81	5.1	0.81
All weeks	6.0	0.47	6.0	0.67	5.9	0.67
Contact with stall elements, %						
Short-term	60.4	8.06	79.2	10.24	41.7	10.24
Mid-term	58.3	8.06	79.2	10.24	37.5	10.24
Long-term	61.5	8.06	72.9	10.24	50.0	10.24
All weeks	60.1	6.77	77.1 [x]	8.16	43.1 [y]	8.16
Attempts of lying, number per lying-down movement						
Short-term	1.0	0.01	1.0	0.02	1.0	0.02
Mid-term	1.0	0.01	1.0	0.02	1.0	0.02
Long-term	1.0	0.01	1.0	0.02	1.0	0.02
All weeks	1.0	0.01	1.0	0.01	1.0	0.01
Hind quarter shifting, %						
Short-term	25.0	5.90	27.1	8.34	22.9	8.34
Mid-term	19.8	5.90	29.2	8.34	10.4	8.34
Long-term	7.3	5.90	14.6	8.34	0.0	8.34
All weeks	17.4	3.85	23.6	5.45	11.1	5.45
Slipping, %						
Short-term	14.6	5.72	16.7	7.76	12.5	7.76
Mid-term	12.5	5.72	12.5	7.76	12.5	7.76
Long-term	20.8	5.72	16.7	7.76	25.0	7.76
All weeks	16.0	4.34	15.3	5.69	16.7	5.69
Overall abnormal lying-down movement, %						
Short-term	67.7 [a]	9.77	77.1	12.67	58.3	12.67
Mid-term	32.3 [b]	9.77	37.5	12.67	27.1	12.67
Long-term	35.4 [b]	9.77	39.6	12.67	31.3	12.67
All weeks	45.1	8.02	51.4	9.92	38.9	9.92

[1]Weeks means within a column with different superscript (a, b, c) differ ($P < 0.05$)
[2]Treatments means within a row with different superscript (x, y, z) differ ($P < 0.05$)
[3]Average across treatments

Supplementary Table 4.2. Quality of rising movements indicators for single and double stall cows (treatment) in the short-, mid- and long-term, and for all weeks (time periods)

	Time Periods[1]		Treatment[2]			
			Single		Double	
	LSmean[3]	SE	Lsmean	SE	LSmean	SE
Duration of rising movement, s						
Short-term	7.9	1.51	8.8	2.14	7.0	2.14
Mid-term	8.3	1.51	9.1	2.14	7.5	2.14
Long-term	8.6	1.51	10.5	2.14	6.6	2.14
All weeks	8.3	1.28	9.5	1.81	7.0	1.81
Attempts, number per rising event						
Short-term	1.3	0.20	1.3	0.24	1.4	0.24
Mid-term	1.3	0.20	1.3	0.24	1.3	0.24
Long-term	1.2	0.20	1.3	0.24	1.2	0.24
All weeks	1.3	0.18	1.3	0.21	1.3	0.21
Backward movement on carpal joints, %						
Short-term	1.3 [a,b]	4.16	0.0	5.88	2.5	5.88
Mid-term	1.0 [a]	4.16	2.1	5.88	0.0	5.88
Long-term	15.6 [b]	4.16	6.3	5.88	25.0	5.88
All weeks	6.0	2.66	2.8	3.76	9.2	3.76
Contact with stall elements, %						
Short-term	33.3	9.48	31.3	13.41	35.4	13.41
Mid-term	33.3	9.48	35.4	13.41	31.3	13.41
Long-term	52.1	9.48	56.3	13.41	47.9	13.41
All	39.6	7.56	41.0	10.69	38.2	10.69
Overall abnormal rising movement, %						
Short-term	50.0	9.31	45.8	13.16	54.2	13.16
Mid-term	47.9	9.31	54.2	13.16	41.7	13.16
Long-term	63.5	9.31	68.8	13.16	58.3	13.16
All weeks	53.8	7.35	56.3	10.40	51.4	10.40

[1]Weeks means within a column with different superscript (a, b, c) differ ($P < 0.05$)
[2]Treatments means within a row with different superscript (x, y, z) differ ($P < 0.05$)
[3]Average across treatments

Supplementary Table 4.3. Postures (upright, back, on ground) of the head during resting (% of resting time) for single and double stall cows (treatment) in the short-, mid- and long-term, and for all weeks (time periods)

	Time Periods[1]		Treatment[2]			
			Single		Double	
	LSmean[3]	SE	Lsmean	SE	LSmean	SE
Upright, % of resting time						
Short-term	91.4	0.73	92.6	0.95	90.3	0.95
Mid-term	90.1	0.73	90.2	0.95	89.9	0.95
Long-term	92.3	0.73	92.9	0.95	91.7	0.95
All weeks	91.3	0.57	91.9	0.68	90.6	0.68
Back, % of resting time						
Short-term	7.8	0.63	6.6	0.89	9.1	0.89
Mid-term	8.6	0.63	9.0	0.89	8.1	0.89
Long-term	6.5	0.63	6.0	0.89	7.1	0.89
All weeks	7.6	0.45	7.2	0.64	8.1	0.64
On ground, % of resting time						
Short-term	0.7	0.52	0.8	0.60	0.6	0.60
Mid-term	1.4	0.52	0.9	0.60	1.9	0.60
Long-term	1.2	0.52	1.2	0.60	1.2	0.60
All weeks	1.1	0.49	0.9	0.53	1.2	0.53

[1]Weeks means within a column with different superscript (a, b, c) differ ($P < 0.05$)
[2]Treatments means within a row with different superscript (x, y, z) differ ($P < 0.05$)
[3]Average across treatments

Supplementary Table 4.4. Postures (tucked, extended) of the front legs during resting (% of resting time) for single and double stall cows (treatment) in the short-, mid- and long-term, and for all weeks (time periods)

	Time Periods[1]		Treatment[2]			
			Single		Double	
	LSmean[3]	SE	Lsmean	SE	LSmean	SE
Tucked posture, % of resting time						
Short-term	94.3	4.08	92.0	4.38	96.6	4.38
Mid-term	92.9	4.08	92.1	4.38	93.7	4.38
Long-term	92.2	4.08	89.2	4.38	95.3	4.38
All weeks	93.1	4.01	91.1	4.25	95.2	4.25
Extended posture, % of resting time						
Short-term	5.6	3.82	7.9	4.13	3.3	4.13
Mid-term	6.6	3.82	7.8	4.13	5.3	4.13
Long-term	7.7	3.82	10.8	4.13	4.6	4.13
All weeks	6.6	3.74	8.8	4.00	4.4	4.00

[1]Weeks means within a column with different superscript (a, b, c) differ ($P < 0.05$)
[2]Treatments means within a row with different superscript (x, y, z) differ ($P < 0.05$)
[3]Average across treatments

Supplementary Table 4.5. Occupation of space (manger, stall, neighboring stall) by the front legs during resting (% of resting time) for single and double stall cows (treatment) in the short-, mid- and long-term, and for all weeks (time periods)

		Time Periods[1]		Treatment[2]			
				Single		Double	
Area		LSmean[3]	SE	Lsmean	SE	LSmean	SE
Manger, % of resting time							
	Short-term	4.3	1.45	7.4	2.05	1.1	2.05
	Mid-term	4.0	1.59	7.0	2.24	1.0	2.24
	Long-term	6.3	1.70	10.6	2.40	2.0	2.40
	All weeks	4.9	1.50	8.4	2.12	1.4	2.12
Stall, % of resting time							
	Short-term	95.3	2.38	92.2	2.87	98.5	2.87
	Mid-term	95.4	2.38	92.6	2.87	98.1	2.87
	Long-term	93.4	2.38	89.2	2.87	97.7	2.87
	All weeks	94.7	2.27	91.3	2.69	98.1	2.69
Neighboring stall, % of resting time							
	Short-term	0.3	0.24	0.3	0.33	0.3	0.33
	Mid-term	0.6	0.24	0.3	0.33	0.8	0.33
	Long-term	0.2	0.24	0.2	0.33	0.3	0.33
	All weeks	0.4	0.16	0.2	0.22	0.5	0.22

[1]Weeks means within a column with different superscript (a, b, c) differ ($P < 0.05$)
[2]Treatments means within a row with different superscript (x, y, z) differ ($P < 0.05$)
[3]Average across treatments

Supplementary Table 4.6. Portrait of the sample of cows used in the study for common outcome measures of welfare (Body Condition Score, Lameness, Cleanliness, Body Injuries, and Milk Production and Quality measures)

	Baseline		**Short-term**		**Mid-term**		**Long-term**	
Outcome measure	Single	Double	Single	Double	Single	Double	Single	Double
Body Condition score, average score	2.56	2.41	2.56	2.41	2.53	2.41	2.66	2.44
Lameness, % cows scored lame	0	13	0	0	13	37.5	38	25
Cleanliness of cows								
Leg, % cows scored dirty	0	0	0	0	0	0	0	0
Flank, % cows scored dirty	0	0	0	0	13	0	13	13
Udder, % cows scored dirty	0	0	0	0	25	0	13	0
Body injuries, % cows injured[1]								
Shoulder	0	0	0	0	0	0	0	0
Flank	0	6	0	6	0	0	0	6
Back	6	0	6	6	6	0	0	6
Hip bone	0	0	0	6	0	0	0	0
Sacrum	0	0	0	0	0	0	0	0
Pin bone	0	6	0	0	0	0	0	6
Hind leg	6	6	6	6	0	13	0	19
Anatomical knee	31	44	44	31	31	44	44	56
Lateral calcaneus (hock)	88	81	100	69	81	75	88	94
Dorsal calcaneus (hock)	0	19	0	0	0	0	6	19
Medial calcaneus (hock)	0	6	0	6	0	6	0	6
Lateral tarsus (hock)	88	69	100	81	94	88	100	88
Medial tarsus (hock)	0	0	0	0	0	0	0	0
Carpal joints (knees)	31	50	25	56	38	38	50	56
Distal neck	0	0	0	0	0	0	0	0
Medial neck	0	0	0	0	0	0	0	0
Proximal neck	13	0	13	0	13	0	13	25
Milk yield, kg/d	40.4	37.4	38.8	36.3	37.1	34.6	37.0	34.4
% with Somatic Cell Count > 200	13	25	13	25	13	13	13	25
Somatic Cell Score, average score	0.93	3.15	1.27	2.88	1.19	2.25	1.72	2.87

[1] % cows with scores 2, 3, and 4 for a given location

CHAPTER 5 – GENERAL DISCUSSION

In Chapter 2, we have seen that chain length and stall width were linked with a few of the various outcome measures of welfare, but that data was scarce, especially in the case of chain length. The current recommendations available in the industry were never validated directly in a scientific context, and while modifying stalls in the direction of meeting them appeared to improve the welfare of dairy cows, the data available does not provide much proof that the recommendations actually suffice to meet the cows' needs for space to fulfill their behavioural need for movement and for rest. Our study fulfilled its objective of investigating the impact of chain length (Chapter 3) and stall width (Chapter 4) on the comfort and the behaviour of tie-stall-housed dairy cows.

In the case of the chain length, we provided data relative to the changes in stall use in cows given longer chains, and showed that cows with longer chains appeared more at ease in their environment, and less hesitant before lying down. Contrary to our hypothesis, cows with longer chains did not increase their use of the space at the back end of their stalls, instead pushing further forward without an impact on cleanliness. While cows seemed more at ease in their surroundings, it appears clear that longer chains cannot fully substitute in for outdoor access or stall-free systems, as they did not result in reduced occurrence of collisions with stall hardware the way the provision of outdoor access does. However, longer chains seem to improve the comfort of dairy cows at the stall with few direct negative outcomes. The implementation of longer chains should however be made carefully, taking into consideration the mobility and the temperament of cows, as well as their previous experience with the set-up. Nonetheless, given the ease with such modifications could be put in place, increasing chain length could be implemented gradually, beginning with younger animals and individuals who are known to adapt easily, as they are more likely to learn to deal with the potential downsides of longer chains such as leg entrapment hazards.

In the case of stall width, our data showed that dairy cows quickly modified their lying behaviour in response to the double width, adopting more lying postures involving the extension of the hind legs further away from the body, and adopting more diverse orientations akin to what was observed in pasture and in loose-pens. Double stalls were also associated with fewer collisions with stall hardware compared to regular stalls fitting the current recommendations, showing that the numbers brought forward as standards for stall width leave very little margin of error to the cows when performing lying-down movements, and may in part be responsible for the increased duration of intention movements and lying-down movements observed in stall-housed animals when compared to stall-free environments. For us, it is likely that dairy cows in all cubicle systems could benefit from wider stalls than currently recommended, although it is unclear how much more width is required to observe the same benefits as in our trial. While our results show that doubling stall width can positively impact the resting capacity of lactating dairy cows, a full application on commercial farms is unlikely, given the potential cost of doubling virtually all stalls overnight. A direct application of the double stall remains possible, but rather as a punctual measure to aid compromised animals recover by granting them with a greater quality of rest and an environment with fewer physical restrictions in close proximity.

Overall, we have learned that chain length and stall width do play a role in modulating the capacity of tie-stall-housed dairy cow to satisfy their need for movement and for rest. The modifications brought forward in the two trials we conducted – increasing chain length by a deviation, or 40 cm, and doubling stall width – appear to fulfill their intended purposes, which were respectively to improve the ease of movement of dairy cows in their environment and to improve the ability to rest of dairy cows. Investigating the impact of these modifications on time periods longer than those of our trials could unveil other benefits, and using intermediate dimensions could aid in identifying optimal dimensions which will satisfy the cows' behavioural needs while meeting with the needs of dairy farmers for economic efficiency.

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APPENDIX A – Variance calculations for all variables analyzed for the chain length trial

Appendix Table A.1 – Random effects variances (σ^2_{row}, σ^2_{cow}, σ^2_e, CS), covariance parameter estimates, phenotypic variance (σ^2_p)[1], variable means ($\bar{x}$)[2], and coefficient of variation (CV)[3] between two chain length treatments, for all variables analyzed that were not taken as a difference from baseline

Variable	σ^2_{row}	σ^2_{cow}	AR(1)	CS	σ^2_e	σ^2_p	$\bar{x}$	CV (%)
Lying Quality Indicators								
Duration of intention movements	0.00	8.33	0.25	-	16.13	24.46	15.42	32.08
Duration of lying motion	-	-	-	-	-	-	-	-
Contact with environment	0.00	0.05	0.31	-	0.04	0.08	0.70	41.36
Attempts of lying	0.00	0.00	-0.03	-	0.00	0.00	1.00	4.28
Hind quarters shifting	0.00	0.03	-0.11	-	0.04	0.07	0.20	133.39
Slipping	-	-	-	-	-	-	-	-
Lying side	0.00	0.00	0.30	-	0.01	0.01	0.51	22.30
Overall abnormal lying	0.00	0.05	0.00	-	0.05	0.11	0.27	120.77
Rising Quality Indicators								
Duration of rising motion	-	-	-	-	-	-	-	-
Attempts of rising	0.00	0.00	0.88	-	1.13	1.13	1.23	86.12
Backward movement on carpal joints	0.00	0.12	0.29	-	0.03	0.15	0.23	167.13
Contact with tie-rail	0.00	0.00	0.13	-	0.02	0.02	0.06	254.40
Delayed Rising	0.00	0.00	-0.04	-	0.00	0.00	0.01	343.25
Overall abnormal rising	0.00	0.12	0.05	-	0.03	0.16	0.30	133.21
Lying behaviours								
Lying time	0.00	4433.12	0.53	-	4585.97	9019.09	710.65	13.36
Number of lying bouts	1.44	3.71	0.49	-	4.86	8.57	13.10	22.35
Duration of lying bouts	47.49	133.52	0.19	-	95.65	229.17	60.03	25.22
Measures of use of space								
Time spent in the rear part of the stall	0.00	0.64	-0.07	-	1.83	2.47	1.87	83.91
Time spent outside of stall by left hip	1.43	52.72	0.43	-	14.47	67.19	10.63	77.08
Minimum distance outside of stall for left hip	-	-	-	-	-	-	-	-
Maximum distance outside of stall for left hip	-	-	-	-	-	-	-	-
Average distance outside of stall for left hip	-	-	-	-	-	-	-	-
Minimum distance outside of stall for right hip	-	-	-	-	-	-	-	-
Maximum distance outside of stall for right hip	-	-	-	-	-	-	-	-
Average distance outside of stall for right hip	26.57	16.06	0.51	-	26.03	42.09	8.59	75.54
Time spent outside of stall by right hip	7.09	8.18	0.24	-	8.46	16.64	5.03	81.16
Minimum distance outside of stall for withers	0.00	0.00	0.25	-	0.01	0.01	0.11	107.51
Maximum distance outside of stall for withers	4.40	18.49	0.19	-	38.47	56.96	14.22	53.08
Average distance outside of stall for withers	0.00	0.80	0.27	-	1.48	2.27	5.01	30.10

Time spent outside of stall by withers	0.00	12.47	0.54	-	8.65	21.12	8.74	52.62
Cow cleanliness, stall cleanliness and bedding quantity								
Leg cleanliness	-	-	-	-	-	-	-	-
Flank cleanliness	0.00	0.00	0.00	-	0.00	0.00	0.99	3.76
Udder cleanliness	0.00	0.00	0.20	-	0.00	0.01	0.96	10.25
Stall cleanliness	0.00	0.00	0.32	-	122.16	122.16	92.24	11.98
Bedding quantity	0.00	62.56	-0.44	-	65.74	128.31	5.73	197.71
Time spent eating/ruminating	0.00	10.50	0.11	-	3.89	14.38	43.02	8.82

[1] $\sigma^2_p = \sigma^2_{cow} + \sigma^2_e$

[2] $\overline{x}$ = the average between the two treatment LSMEANS

[3] CV = (sqrt (σ^2_p)/ $\overline{x}$) * 100

Appendix Table A.2. Mean ± SEM, variance, and coefficient of variation (CV)[1] for all analyzed study variables not analyzed as a difference from baseline

Table A6. Mean ± SEM, variance, and coefficient of variation (CV)[1] for all analyzed study variables

Variable	**Mean ± SEM**	**σ^2**	**CV**
Lying Quality Indicators			
Duration of intention movements	15.42 ± 15.42	28.862	1.872
Duration of lying motion	8.71 ± 1.33	241.091	27.686
Contact with environment	0.70 ± 0.02	0.073	0.104
Attempts of lying	1.00 ± 0.004	0.002	0.002
Hind quarters shifting	0.20 ± 0.02	0.074	0.376
Slipping	0.11 ± 0.02	0.053	0.489
Lying side	0.51 ± 0.01	0.014	0.027
Overall abnormal lying	0.27 ± 0.03	0.097	0.359
Rising Quality Indicators			
Duration of rising motion	10.80 ± 1.11	168.811	15.637
Attempts of rising	1.23 ± 0.07	0.697	0.565
Backward movement on carpal joints	0.23 ± 0.03	0.111	0.48
Contact with tie-rail	0.06 ± 0.01	0.02	0.353
Delayed Rising	0.02 ± 0.01	0.003	0.209
Overall abnormal rising	0.30 ± 0.03	0.124	0.417
Lying behaviours			
Lying time	710.65 ± 9.30	11677.52	16.432
Number of lying bouts	13.10 ± 0.32	14.098	1.076
Duration of lying bouts	60.03 ± 1.80	436.794	7.276
Measures of use of space			
Time spent in the rear part of the stall	1.87 ± 0.22	6.898	3.683
Time spent outside of stall by left hip	10.64 ± 0.68	64.342	6.05
Minimum distance outside of stall for left hip	0.25 ± 0.05	0.284	1.153
Maximum distance outside of stall for left hip	47.90 ± 4.85	3266.518	68.19
Average distance outside of stall for left hip	12.75 ± 0.73	74.501	5.842
Minimum distance outside of stall for right hip	0.43 ± 0.09	1.042	2.453
Maximum distance outside of stall for right hip	31.37 ± 4.01	2239.313	71.376
Average distance outside of stall for right hip	8.59 ± 0.57	44.899	5.228
Time spent outside of stall by right hip	5.03 ± 0.44	26.51	5.275
Minimum distance outside of stall for withers	0.11 ± 0.01	0.015	0.138
Maximum distance outside of stall for withers	14.22 ± 0.67	63.2	4.445
Average distance outside of stall for withers	5.01 ± 0.18	4.243	0.847
Time spent outside of stall by withers	8.74 ± 0.51	35.434	4.056
Cow cleanliness, stall cleanliness and bedding quantity			
Leg cleanliness	-	-	-
Flank cleanliness	0.99 ± 0.01	0.001	0.001
Udder cleanliness	0.96 ± 0.02	0.009	0.01
Stall cleanliness	92.24 ± 1.77	100.288	1.087
Bedding quantity	5.73 ± 1.92	118.448	20.674
Time spent eating/ruminating	43.02 ± 0.57	35.77	0.831

[1]CV = $\sigma / \bar{x}$

Appendix Table A.3. Matrix compiling the variances (diagonal), co-variances (above the diagonal) and correlations (below the diagonal) for the 6 weeks analyzed on the duration of lying motion

	Week 1	Week 2	Week 3	Week 6	Week 8	Week 10
Week 1	1376.0500	9.6869	8.3329	-24.1381	-0.3602	5.2335
Week 2	0.1212	4.6439	4.2014	7.5013	2.3440	2.6465
Week 3	0.1091	0.9468	4.2400	6.6384	2.2888	2.5908
Week 6	-0.0767	0.4104	0.3801	71.9269	3.8052	5.7911
Week 8	-0.0079	0.8800	0.8993	0.3630	1.5277	1.2274
Week 10	0.0969	0.8434	0.8641	0.4689	0.6820	2.1204

Appendix Table A.4. Matrix compiling the variances (diagonal), co-variances (above the diagonal) and correlations (below the diagonal) for the 6 weeks analyzed on slipping during lying motion

	Week 1	Week 2	Week 3	Week 6	Week 8	Week 10
Week 1	0.1295	0.0789	0.0972	0.1142	0.1142	0.0588
Week 2	0.7286	0.0905	0.0586	0.0773	0.0714	0.0437
Week 3	0.9238	0.6660	0.0854	0.0976	0.1026	0.0280
Week 6	0.7766	0.6286	0.8173	0.1670	0.1321	0.0698
Week 8	0.8543	0.6386	0.9450	0.8702	0.1380	0.0301
Week 10	0.5914	0.5261	0.3472	0.6185	0.2929	0.0763

Appendix Table A.5. Matrix compiling the variances (diagonal), co-variances (above the diagonal) and correlations (below the diagonal) for the 6 weeks analyzed on the duration of rising motion

	Week 1	Week 2	Week 3	Week 6	Week 8	Week 10
Week 1	61.1617	68.2583	97.0338	110.9000	108.1000	145.4100
Week 2	0.9835	78.7535	112.6600	130.7300	124.0100	165.7700
Week 3	0.9127	0.9338	184.8200	220.0700	191.7300	267.5400
Week 6	0.8673	0.9010	0.9901	267.3000	228.7800	320.6300
Week 8	0.9479	0.9583	0.9672	0.9596	212.6300	288.2700
Week 10	0.9287	0.9330	0.9830	0.9795	0.9874	400.8300

Appendix Table A.6. Matrix compiling the variances (diagonal), co-variances (above the diagonal) and correlations (below the diagonal) for the 6 weeks analyzed on the minimum distance outside stall for left hip

	Week 1	Week 2	Week 3	Week 6	Week 8	Week 10
Week 1	0.1420	0.0505	0.0159	0.0689	0.0456	0.0956
Week 2	0.7093	0.0357	0.0010	0.0365	0.0417	0.0613
Week 3	0.1984	0.0239	0.0451	0.0097	0.0030	0.0190
Week 6	0.3436	0.3631	0.0862	0.2833	0.1796	0.2092
Week 8	0.1516	0.2760	0.0176	0.4223	0.6384	0.7193
Week 10	0.2775	0.3545	0.0979	0.4299	0.9848	0.8357

Appendix Table A.7. Matrix compiling the variances (diagonal), co-variances (above the diagonal) and correlations (below the diagonal) for the 6 weeks analyzed on the maximum distance outside stall for left hip

	Week 1	**Week 2**	**Week 3**	**Week 6**	**Week 8**	**Week 10**
Week 1	5774.1300	5863.5500	6398.9500	6321.6000	6573.7500	5362.0100
Week 2	0.9952	6011.4700	6451.2700	6535.5000	6734.1600	5508.1200
Week 3	0.9390	0.9278	8042.7300	6984.2000	7194.5600	7336.5600
Week 6	0.9174	0.9295	0.8588	8223.4500	7511.2700	6982.1400
Week 8	0.9891	0.9930	0.9172	0.9470	7650.4100	6198.6700
Week 10	0.7806	0.7859	0.9050	0.8518	0.7840	8171.0100

Appendix Table A.8. Matrix compiling the variances (diagonal), co-variances (above the diagonal) and correlations (below the diagonal) for the 6 weeks analyzed on the average distance outside stall for left hip

	Week 1	**Week 2**	**Week 3**	**Week 6**	**Week 8**	**Week 10**
Week 1	63.7345	44.7317	114.5900	55.5309	42.9483	149.3200
Week 2	0.8975	32.6215	79.0862	39.1585	31.5839	106.7900
Week 3	0.9489	0.9163	209.1100	102.8200	79.6337	275.6000
Week 6	0.8332	0.8221	0.8909	63.6969	43.9887	144.7600
Week 8	0.7966	0.8197	0.8530	0.8537	41.6803	112.1900
Week 10	0.9102	0.9108	0.9701	0.9233	0.8846	385.9400

Appendix Table A.9. Matrix compiling the variances (diagonal), co-variances (above the diagonal) and correlations (below the diagonal) for the 6 weeks analyzed on the minimum distance outside stall for right hip

	Week 1	**Week 2**	**Week 3**	**Week 6**	**Week 8**	**Week 10**
Week 1	0.2915	0.0254	0.0315	0.0648	0.0445	0.0161
Week 2	0.0217	4.6842	1.1002	-0.1121	-0.3950	0.3722
Week 3	0.0972	0.8470	0.3602	0.0520	-0.1313	0.1602
Week 6	0.2402	-0.1037	0.1735	0.2494	-0.0625	0.1006
Week 8	0.1317	-0.2918	-0.3497	-0.2000	0.3913	-0.1363
Week 10	0.0745	0.4293	0.6663	0.5028	-0.5439	0.1605

Appendix Table A.10. Matrix compiling the variances (diagonal), co-variances (above the diagonal) and correlations (below the diagonal) for the 6 weeks analyzed on the maximum distance outside stall for right hip

	Week 1	**Week 2**	**Week 3**	**Week 6**	**Week 8**	**Week 10**
Week 1	2178.1400	702.7700	2195.7800	2134.3500	2407.6600	1083.7400
Week 2	0.8252	332.9600	768.2100	988.4200	1084.3700	-35.7482
Week 3	0.8277	0.7406	3231.1100	3297.0100	3499.9300	4126.7500
Week 6	0.7105	0.8416	0.9012	4142.6700	4349.2800	1313.4900
Week 8	0.7565	0.8473	0.9028	0.9908	4650.9400	1346.1600
Week 10	0.3615	-0.0305	1.1301	0.3177	0.3073	4126.7500

APPENDIX B – Variance calculations for all variables analyzed for the stall width trial

Appendix Table B.1. Random effects variances (σ^2_{row}, σ^2_{cow}, σ^2_e, CS), covariance parameter estimates, phenotypic variance (σ^2_p)[1], variable means ($\bar{x}$)[2], and coefficient of variation (CV)[3] between two stall width treatments, for all variables analyzed and not taken as a difference from baseline

Variable	σ^2_{row}	σ^2_{cow}	AR(1)	CS	σ^2_e	σ^2_p	$\bar{x}$	CV (%)
Lying Quality Indicators								
Duration of intention movements	470.20	1353.05	-0.99	-	1422.85	2775.90	25.90	203.46
Duration of lying motion	0.00	3.30	-0.70	-	1.93	5.24	5.96	38.41
Contact with environment	0.01	0.02	-0.04	-	0.04	0.06	0.60	42.02
Attempts of lying	0.00	0.00	-0.06	-	0.00	0.00	1.00	5.01
Hind quarters shifting	0.00	0.00	0.24	-	0.06	0.06	0.17	135.89
Slipping	0.00	0.01	0.14	-	0.03	0.04	0.16	131.15
Dog Sitting	-	-	-	-	-	-	-	-
Overall abnormal lying	0.01	0.00	0.44	-	0.10	0.10	0.45	71.58
Rising Quality Indicators								
Duration of rising motion	0.00	22.43	0.49	-	14.22	36.65	8.25	73.38
Attempts of rising	0.04	0.17	-0.57	-	0.13	0.29	1.28	42.39
Backward movement on carpal joints	0.00	0.00	0.25	-	0.03	0.03	0.06	278.63
Contact with tie-rail	0.00	0.00	0.59	-	0.14	0.14	0.40	95.80
Delayed Rising	-	-	-	-	-	-	-	-
Overall abnormal rising	0.00	0.00	0.57	-	0.14	0.14	0.54	69.17
Lying behaviours								
Lying time	0.00	0.00	0.78	-	6391.55	6391.55	691.81	11.56
Number of lying bouts	0.00	0.00	0.33	-	2.71	2.71	12.74	12.92
Duration of lying bouts	0.00	57.72	-0.08	-	33.18	90.90	57.28	16.65
Lying postures								
Side, right	0.00	160.03	-0.14	-	222.29	382.32	52.30	37.39
Side, left	0.00	158.67	-0.14	-	222.28	380.95	47.72	40.90
Body, lying on side	-	-	-	-	-	-	-	-
Body, lying on sternum	-	-	-	-	-	-	-	-
Head, upright	0.37	0.00	0.17	-	5.66	5.66	91.25	2.61
Head, back	0.00	1.97	0.11	-	4.32	6.29	7.65	32.80
Head, on ground	0.38	0.51	0.01	-	0.84	1.35	1.09	106.47
Front leg, tucked	28.14	28.20	0.29	-	12.36	40.56	93.14	6.84
Front leg, extended	24.14	27.26	0.39	-	12.56	39.82	6.60	95.61
Hind leg, tucked	0.00	35.47	-0.02	-	35.23	70.70	83.33	10.09
Hind leg, mid-position	3.70	16.27	-0.29	-	15.05	31.32	9.09	61.56
Hind leg, extended	0.00	0.00	0.50	-	35.97	35.97	7.33	81.85
Position of head, body and limbs in space								
Head, divider	-	-	-	0.00	0.00	0.00	0.01	692.75
Head, manger area	0.00	227.67	-0.46	-	139.52	367.19	57.60	33.27
Head, stall	6.20	0.00	0.62	-	256.01	256.01	34.91	45.84
Head, neighboring stall	11.48	26.89	-0.30	-	84.16	111.05	7.48	140.94
Front leg, manger	-	-	-	-	-	-	-	-
Front leg, stall	6.04	30.56	0.39	-	11.41	41.97	94.72	6.84
Front leg, neighboring stall	0.01	0.29	-0.60	-	0.54	0.83	0.36	251.81
Hind legs, stall	3.65	1.06	0.38	-	38.71	39.77	88.67	7.11
Hind legs, neighboring stall	0.00	0.00	-0.07	-	9.77	9.77	7.97	39.20

Hind legs, gutter area	-	-	-	-	-	-	-	-
Cow cleanliness, stall cleanliness and bedding quantity								
Leg cleanliness	0.00	19.84	-0.31	-	60.00	79.83	96.88	9.22
Flank cleanliness	102.83	0.00	-0.17	-	80.96	80.96	92.71	9.71
Udder cleanliness	0.00	29.63	-0.48	-	143.28	172.91	94.79	13.87
Stall cleanliness	41.39	0.00	0.60	-	42.83	42.83	91.16	7.18
Bedding quantity	0.00	0.00	0.06	-	163.08	163.08	29.76	42.92
Time spent eating/ruminating	8.93	7.27	-0.04	-	2.54	9.80	54.62	5.73

[1]$\sigma^2_p = \sigma^2_{cow} + \sigma^2_e$

[2]$\overline{x}$ = the average between the two treatment LSMEANS

[3]CV = (sqrt (σ^2_p)/ $\overline{x}$) * 100

Appendix Table B.2. Mean ± SEM, variance, and coefficient of variation (CV)[1] for all analyzed study variables not taken as a difference from baseline

Variable	Mean ± SEM	σ^2	CV
Lying Quality Indicators			
Duration of intention movements	25.90 ±6.49	2021.710	78.071
Duration of lying motion	5.96 ± 0.27	3.615	0.607
Contact with environment	0.60 ± 0.04	0.091	0.151
Attempts of lying	1.00 ± 0.01	0.003	0.003
Hind quarters shifting	0.17 ± 0.04	0.072	0.415
Slipping	0.16 ± 0.03	0.043	0.266
Dog Sitting	-	-	-
Overall abnormal lying	0.45 ± 0.05	0.131	0.291
Rising Quality Indicators			
Duration of rising motion	8.25 ±0.87	36.064	4.371
Attempts of rising	1.28 ± 0.07	0.258	0.202
Backward movement on carpal joints	0.06 ± 0.03	0.033	0.547
Contact with tie-rail	0.40 ± 0.05	0.127	0.321
Delayed Rising	-	-	-
Overall abnormal rising	0.54 ± 0.05	0.134	0.249
Lying behaviours			
Lying time	691.82 ± 15.30	10528.700	15.219
Number of lying bouts	12.74 ± 0.36	5.725	0.449
Duration of lying bouts	57.28 ± 2.07	192.504	3.361
Lying postures			
Side, right	52.30 ± 2.91	407.177	7.785
Side, left	47.72 ± 2.91	406.646	8.522
Body, lying on side	0.18 ± 0.18	0.532	2.966
Body, lying on sternum	99.80 ± 0.11	0.545	0.005
Head, upright	91.25 ± 0.37	6.515	0.071
Head, back	7.65 ± 0.36	6.190	0.810
Head, on ground	1.09 ± 1.09	1.419	1.300
Front leg, tucked	93.14 ± 0.94	42.001	0.451
Front leg, extended	6.60 ± 0.92	40.468	6.131
Hind leg, tucked	83.33 ± 1.28	78.901	0.947
Hind leg, mid-position	9.09 ± 0.78	29.343	3.228
Hind leg, extended	7.33 ± 0.99	47.119	6.430
Position of head, body and limbs in space			
Head, divider	0.01 ± 0.01	0.002	0.284
Head, manger area	57.60 ± 3.75	675.638	11.730
Head, stall	34.91 ± 3.41	557.663	15.976
Head, neighboring stall	7.48 ± 1.55	114.925	15.371
Front leg, manger	4.87 ± 0.95	42.949	8.821
Front leg, stall	94.72 ± 0.96	44.622	0.471
Front leg, neighboring stall	0.36 ± 0.13	0.775	2.140
Hind legs, stall	88.67 ± 1.23	73.140	0.825
Hind legs, neighboring stall	7.97 ± 1.15	64.030	8.031
Hind legs, gutter area	3.36 ±0.94	42.667	12.717
Cow cleanliness, stall cleanliness and bedding quantity			
Leg cleanliness	96.88 ± 1.72	71.332	0.736
Flank cleanliness	92.71 ± 2.37	134.737	1.453
Udder cleanliness	94.79 ± 2.50	161.911	1.708
Stall cleanliness	91.16 ±1.95	91.259	1.001
Bedding quantity	29.76 ± 4.04	392.601	13.194
Time spent eating/ruminating	54.62 ± 0.53	19.910	0.365

[1]CV = $\sigma / \bar{x}$

Appendix Table B.3. Matrix compiling the variances (diagonal), co-variances (above the diagonal) and correlations (below the diagonal) for the 3 weeks analyzed on the lying on side posture

	Week 1	**Week 3**	**Week 6**
Week 1	0.0051	0.0472	-0.0043
Week 3	0.5670	1.3694	0.1277
Week 6	-0.2631	0.4739	0.0530

Appendix Table B.4. Matrix compiling the variances (diagonal), co-variances (above the diagonal) and correlations (below the diagonal) for the 3 weeks analyzed on the lying on sternum posture

	Week 1	**Week 3**	**Week 6**
Week 1	0.0051	0.0425	-0.0043
Week 3	0.5236	1.3041	0.1195
Week 6	-0.2631	0.4545	0.0530

Appendix Table B.5. Matrix compiling the variances (diagonal), co-variances (above the diagonal) and correlations (below the diagonal) for the 3 weeks analyzed on the front legs in manger position in space

	Week 1	**Week 3**	**Week 6**
Week 1	33.5458	35.8107	32.1667
Week 3	0.9746	40.2464	33.0507
Week 6	0.8168	0.7662	46.2317