Effect of Positioning the Tie-rail to Follow the Natural Neck Line of Cows when Eating and Rising on the Welfare of Dairy Cows Housed in Tie-stall Barns

BY

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SEPTEMBER 2018

A thesis submitted to the McGill University in partial fulfillment of the requirements of the degree of

Master of Science

In

Animal Science

ABSTRACT

A majority of dairy farms in Canada are tie-stall barns, but few experimental studies have investigated ways to improve cow comfort through tie-stall design. Epidemiological studies have found that tie-stall design may have an effect on dairy cow welfare, such as body injuries and lying time. A recent epidemiological study found that when current recommendation for tie-rail height is met or exceeded, the risk of neck injuries and lameness increased and lying time and bout frequency decreased. However, when tie-rail met or exceeded current recommendation for tie-rail forward position, there was a reduced risk of neck and knee injuries and lameness and increase in bout frequency, but there was an increased risk of dirty udders. Therefore, our objective was to investigate tie-rail placement and develop new recommendations that combine both height and forward positions to improve dairy cow welfare, and to help farmers meet their targets for the animal care assessment implemented by the Dairy Farmers of Canada through the proAction® initiative.

For this study we tested two new tie-rail positions that follow the natural neck line of dairy cows when they are feeding and rising, as it is likely cows come in contact with the tie-rail during these events. Thus, four treatments were tested: two new tie-rail positions that follow the neck line of cows (Neckline1, Neckline2), Current Recommendation, and the tie-rail position commonly found on farm (Common on Farm). All other stall dimensions followed current recommendation based on cow size. Forty-eight cows blocked by parity and stage of lactation were divided between two start dates and randomly allocated to a treatment for 10 weeks. Live scoring was performed weekly to evaluate: injury, cow and stall cleanliness, bedding quantity, and body condition. Lameness scoring was performed weekly through video observation. Milk yields were recorded at each milking and milk samples were collected weekly to evaluate milk components. Feeding/rumination time was recorded continuously for 24 cows equally distributed across treatments, using ear-mounted activity data loggers. Resting behaviours, such as daily lying time, lying bout frequency, and duration of lying bouts, were continuously recorded using leg mounted accelerometers. Cows were recorded 1 d/wk by overhead cameras and 6 lying and rising events were evaluated per recording. Differences over time were analyzed using a mixed model with a Scheffé adjustment for multiple comparisons and a Dunnett adjustment to compare Neckline1, Neckline2, and Common on Farm treatments to Current Recommendation.

The tie-rail positions tested did not have an effect on cow and stall cleanliness, bedding quantity, body condition, lameness, milk yield and components, feeding/rumination time, rising and lying ability, and resting behaviour. However, Current Recommendation (difference from wk 0: +0.9 ± 0.16) had an increase in proximal neck injuries compared to Neckline2 (+0.1 ± 0.15; $P \leq 0.05$). Neckline2 (+0.8 ± 0.16) and Neckline1 (+0.5 ± 0.16) had an increase in medial neck injuries compared to the Current Recommendation (-0.1 ± 0.18; $P \leq 0.05$). All treatments showed a decrease over time in average lying intention time (-5.9 s/event; $P \leq 0.05$), lying-down time (-1.1 s/event; $P \leq 0.05$), contact with stall (-32.5 %; $P \leq 0.05$) and slipping (-9.4 %; $P \leq 0.05$) during lying motion. All treatments showed a decrease over time in average backwards movement on knees (-10.8 %; $P \leq 0.05$) and contact with tie-rail (-14.3 %; $P \leq 0.05$) during rising motion and overall abnormal rising (-15.7 %; $P \leq 0.05$). Although, lying and rising ability improved over time, the prevalence of abnormal lying and rising was still high in the long-term for all treatments; for example, in the long-term, cows still came in contact with the stall dividers or tie-rail 42.3% of the time during lying motion.

Results suggest that the injury location on the neck shifts based on tie-rail placement. For all tie-rail positions lying and rising ability improved over time, however abnormal lying and rising behaviours were still highly prevalent across treatments. Thus, further research is needed to improve stall design to reduce injuries and abnormal lying and rising behaviours. For instance, studies investigating alternative options to stall design such as a different material apposed to metal bars (e.g., a flexible bar or chain) and/or increasing the tie-rail forward position even further may reduce contacts between the bar and the cows. Alternatively, housing options providing fewer obstacles in the cow’s environment through the elimination of stall hardware should be investigated such as a deep-bedded pack or compost pack.

RESUMÉ

Bien que la majorité des fermes laitières canadiennes logent leurs animaux en stabulation entravée, il n’existe que très peu de données à propos du confort des vaches dans ce type de système. Bien que des données issues d’études épidémiologiques récentes aient identifié un lien entre la configuration des stalles et diverses mesures du bien-être des vaches comme les blessures corporelles et le temps de repos, très peu d’essais contrôlés ont été conduits pour identifier comment des changements à la configuration des stalles pourraient améliorer le confort des vaches en stabulation entravée. Les récentes données épidémiologiques ont montré que lorsque la barre d’attache est à la hauteur recommandée ou positionnée plus haut, les risques de blessures au cou et de boiterie sont plus élevés, et le temps de repos ainsi que le nombre d’épisodes de repos par jour diminuent. D’un autre côté, lorsque la barre est avancée au niveau recommandé, ou plus éloignée, les risques de boiterie et de blessures au cou et aux genoux sont plus faibles, et le nombre d’épisodes de repos par jour, quant à lui, augmente, mais les risques d’avoir des pis sales augmentent aussi. Par conséquent, notre objectif était d’évaluer l’impact de la position de la barre d’attache, et de développer de nouvelles recommandations combinant à la fois la hauteur et l’avancement de la barre, et ainsi aider les producteurs laitiers à améliorer le bien-être de leurs vaches et à rencontrer les objectifs qui leur sont imposés dans le cadre du programme ProAction® mis en place par les Producteurs Laitiers du Canada.

Durant ce projet de recherche, nous avons évalué deux nouvelles positions de la barre d’attache suivant la pente formée par le cou de la vache lorsqu’elle s’alimente et lorsqu’elle se lève, puisque c’est lors de ces activités que les vaches entrent le plus souvent en contact avec la barre d’attache. Ainsi, quatre traitements ont été mis à l’essai : les deux nouvelles positions suivant la pente naturelle du cou (Neckline 1 & Neckline 2), la recommandation actuelle (Current Recommendation) et la position la plus communément trouvée sur les fermes laitières, présentement (Common on Farm). Toutes les autres dimensions de la stalle correspondaient aux recommandations actuelles, qui sont basées sur les mensurations des vaches. 48 vaches laitières, regroupées par quatre selon le nombre de vêlages et le stade de lactation, ont été divisées entre deux dates de début de projet et assignées au hasard à l’un des quatre traitements pour un total de 10 semaines. Les blessures corporelles, la propreté des vaches et des stalles, la quantité de litière et la condition de chair des vaches ont été évaluées par des observations directes chaque semaine

durant tout le projet. L'évaluation hebdomadaire de la boiterie, quant à elle, a été réalisée via l'observation de vidéos des vaches du projet. Le rendement laitier des vaches était enregistré automatiquement lors de chacune des traites, et des échantillons de lait collectés chaque semaine ont permis d'évaluer les diverses composantes laitières. Le temps total consacré à l'alimentation et/ou à la rumination a été évalué en continu à l'aide de moniteurs d'activité attachés dans l'oreille de 6 vaches par traitement (pour un total de 24 vaches). Des accéléromètres posés sur les pattes des vaches ont permis de recueillir des données sur les comportements de repos, notamment le temps total de repos, le nombre d'épisodes de repos, ainsi que la durée des épisodes de repos. 6 mouvements de lever et 6 mouvements de coucher par semaine ont été évalués, grâce aux données vidéo enregistrées par des caméras situées au-dessus des stalles. Chacune des vaches était filmée par ces caméras durant une période totalisant 24h par semaine. Les différences entre les court, moyen et long termes ont été analysées à l'aide d'un modèle mixte, avec un ajustement de Scheffé pour tenir compte des comparaisons multiples. Pour comparer les traitements « Neckline 1 », « Neckline 2 » et « Common on Farm » à la recommandation actuelle (« Current Recommendation »), un test de Dunnett a été effectué.

La position de la barre d'attache n'a pas eu d'impact sur la propreté des vaches ni des stalles, pas plus que sur la quantité de litière, la condition de chair, la boiterie, la production de lait et les composantes laitière, le temps consacré à l'alimentation et/ou la rumination, l'aisance des vaches au lever et au coucher, ni sur les comportements de repos. Cependant, les niveaux de blessures dans la région proximale du cou ont augmenté chez la recommandation actuelle (différence par rapport à la semaine 0 : +0,9 ± 0,16), par rapport au traitement Neckline2 (+0,1 ± 0,15; $P \leq 0{,}05$). Du côté des blessures dans la région médiale du cou, les niveaux de blessures ont augmenté chez traitements Neckline2 (+0,8 ± 0,16) et Neckline1 (+0,5 ± 0,16), par rapport à la recommandation actuelle (-0,1 ± 0,18; $P \leq 0{,}05$). La durée de la phase de préparation au coucher a diminué au fil du temps pour tous les traitements (-5,9 s/coucher; $P \leq 0.05$), de même que la durée du mouvement de coucher (-1,1 s/coucher; $P \leq 0.05$), la fréquence des contacts avec les éléments de la stalle (-32,5%; $P \leq 0.05$) et la glissade des pieds (-9,4%; $P \leq 0.05$) durant les mouvements de coucher. Du côté des mouvements de lever, la fréquence des mouvements arrière sur les genoux (-10,8%; $P \leq 0.05$), des contacts avec la barre d'attache (-14,3%; $P \leq 0.05$) et la proportion de levers anormaux (-15,7%; $P \leq 0.05$) ont diminué au fil du temps, pour tous les traitements. Cependant, bien que l'aisance des vaches au lever et au coucher se soient améliorées au fil du temps, la prévalence des levers et des couchers anormaux est demeurée élevée, à long terme, pour tous les traitements. Par exemple, à la fin de l'expérience, les vaches entraient encore en contact avec les éléments de la stalle lors de 42,3% des mouvements de coucher.

Ces résultats semblent montrer que la position des blessures au cou est liée à celle de la barre d'attache. Puisque, malgré une amélioration au fil des semaines, la prévalence des levers et couchers anormaux est demeurée élevée pour tous les traitements. Il semble que plus d'efforts de recherche soient nécessaires pour améliorer la configuration des stalles, de façon à diminuer les niveaux de blessures et les mouvements de lever et de coucher anormaux. Des exemples de pistes à suivre incluent des alternatives à la barre d'attache traditionnelle, notamment des chaînes ou des barres flexibles, ainsi que l'évaluation de positions plus extrêmes, notamment des barres avancées encore plus loin que la recommandation actuelle, lesquelles pourraient potentiellement diminuer le nombre de contacts entre les vaches et la barre d'attache. D'autres options de logement telles que les parcs de litière profonde ou de litière compostée, qui sont dépourvues des barres et diviseurs définissant les stalles, pourraient également constituer des solutions, puisqu'elles fournissent aux vaches un environnement comportant moins d'obstacles.

ACKNOWLEDGEMENTS

I would like to acknowledge everyone who assisted me in completing this Master's thesis. Foremost, I would like to express my deepest appreciation and gratitude to my supervisor, Dr. Elsa Vasseur, whose guidance and constant support was invaluable and drove me to do my best during my Master's. You have been an excellent mentor and you have inspired me in all aspects of life. I would also like to thank Dr. Jeff Rushen and Dr. Kevin Wade, members of my committee, for their support and guidance during my masters and for reviewing my progress and manuscripts.

I would like to sincerely thank Dr. Roger Cue for his assistance with statistical design, guidance relating to my many questions concerning statistical analysis, and support throughout my Master's. Special thanks to Steve Adam a dairy cow welfare expert from Valacta for his assistance with study design.

I am very grateful for the assistance and support of all the members of Vasseur's lab. I would like to sincerely thank Tania Wolfe for her assistance in project planning and data collection and for her advice and support throughout this project. I would also like to thank Elise Shepley for always being there to advise and support me and for assisting with data collection. Special thanks to Sarah McPherson for assisting in reviewing and editing the manuscript. I want to thank all the research assistances who aided with data collection and entry throughout this project: Paul Stecko, Géraud Plas-Debecker, Marianne Berthelot, Véronique Boyer, Sirine El hamdaoui, Anthony Pic, Brittany Talarico, Elyse Perrault, Athena Zambelis, Mathias Gagnon-Barbin, Emile Royer, and Morgane Morandeau.

I am very thankful to Canadian Dairy Commission in collaboration with Novalait for granting me a graduate student award. I would also like to sincerely thank Natural Sciences and Engineering Research Council of Canada (NSERC), Novalait, Dairy Farmers of Canada, and Valacta for their financial aid via Vasseur's Industrial Research Chair.

Lastly, I would like to thank my friends and family, specifically my parents Connie and Steven and my partner Travis for their love and support throughout my Master's. Without their love and encouragement my Master's thesis may not have come to fruition.

CONTRIBUTION OF AUTHORS

Authors of the presented manuscript

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Dr. Elsa Vasseur designed and organized the experiment and supervised the primary author. Dr. Jeff Rushen provided his assistance and support with interpretation of the experiments results and reviewing manuscripts. Steve Adam assisted with the experimental design and the interpretation of the experiments results. Jessica St John conducted the experiment, analyzed the data, wrote the manuscript, and assisted with experimental design.

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CHAPTER 1. GENERAL INTRODUCTION

According to recent surveys, the general public has demonstrated a heightened awareness of dairy cattle welfare in both Canada and the U.S. (Schuppli et al., 2014; Cardoso et al., 2016). These surveys have found that the general public is not only concerned with the biological functioning of the animal, but is also now placing a greater importance on cows' ability to express natural behaviours (Cardoso et al., 2016). The increase in public concern for dairy cow welfare has led to the implementation of animal care assessments through certification programs, such as the proAction® initiative implemented by Dairy Farmers of Canada. Thus, research to develop new recommendations leading to the improvement of dairy cow welfare is important to help producers meet the high standards set in the Canadian Code of Practice for the care and handling of dairy cattle (Dairy Farmers of Canada (DFC) - National Farm Animal Care Council (NFACC), 2009).

A majority of Canadian dairy cows are housed in indoor confinement therefore the effect of the housing conditions on their welfare is important. Typical housing system for cows include an individual bed which we call a stall. Stall configuration has been linked to outcome measures of welfare such as injuries, changes in lying behaviours and cleanliness (Zurbrigg et al., 2005; Heyerhoff et al., 2014; Bouffard et al., 2017). However, few experimental studies have been conducted on tie-stall configuration. Thus, there is an opportunity here to support dairy cow welfare on farm through stall configuration improvement. The effect of stall configuration on tie-stall housed cows could be considered doubly important since cows spend majority of their time in the stall. Additionally, 74.4% of dairy cows in Canada and 92.8% in Quebec are housed in tie-stall barns (Canadian Dairy Information Centre, 2017). There are many aspects of stall configuration such as stall width and length, chain length and tie-rail height and forward position. One aspect of stall configuration that requires further investigation is tie-rail height and forward position. The tie-rail is used as a visual and physical barrier at the front of the stall. An epidemiological study on tie-stall farms found that when the tie-rail met current recommendation for forward position, there was a decreased risk of neck and knee injuries and lameness, and the number in lying bouts increased, although there was also an increased risk of dirty udders (Bouffard et al., 2017). When the tie-rail met current recommendation for height the risk of neck injuries and lameness increased and lying time decreased (Bouffard et al., 2017). Thus, the current recommendation for tie-rail height may reduce dairy cow welfare. Additionally, Bouffard et al. (2017) found that there is a 33% prevalence of neck injuries on tie-stall Canadian dairy farms. These injuries may be the result of improper tie-rail placement leading to regular contacts between the cow’s neck and the tie-rail. Thus, there is a need to investigate tie-rail positions which will improve the welfare of dairy cows on farm.

1.1 Hypothesis and implications

As mentioned above, there is a high prevalence of neck injuries on Canadian tie-stall dairy farms and the current recommendation for tie-rail height may reduce dairy cow welfare. The prevalence of neck injuries on Canadian tie-stall dairy farms could be due to dairy cows coming in contact with the tie-rail, which is thought to occur when cows are rising and pressing on the tie-rail when they are eating. Thus, it is hypothesized that positioning the tie-rail to follow the slope of a cow’s neck line when they are rising and feeding will limit contact with the tie-rail, allowing dairy cows to move more naturally in their stall leading to improved welfare. If this hypothesis is true then tie-rails that are positioned to follow the cow’s neck line when they are rising and feeding will improve cow’s ease of movement in her stall. Improvements to the cow’s ease of movement can be observed through: an increase in lying time and number of lying bouts, a decrease in lying bout duration and an improvement in lying-down and rising ability. The increased ability of movement should also result in a reduction of dairy cow injuries, in this case especially neck injuries. We will also be observing the tie-rail’s effect on lameness, cow and stall cleanliness, body condition, eating/rumination time, and milk yield and components, as these are common outcome measures of welfare reported in studies investigating stall configuration. We predict that lameness may be reduced when the tie-rail is positioned to follow the neck line of cows when they are rising and feeding. We hypothesize that stall and cow cleanliness will improve when tie-rail is positioned closer to the cow, such as one of the new tie-rail positions that follows the cow’s neck line when rising and feeding and tie-rail position commonly found on farm. We also predict that positioning the tie-rail to follow the neck line of the cows will not affect body condition, eating/rumination time, or milk yield and components.

This thesis will cover a literature review on the functions, recommendations and effects of the tie-rail in tie-stall barns, and its counterpart neck-rail and feed-rail in free-stall barns, on dairy cow welfare. Next, an experimental study will be presented comparing current recommendation for tie-rail placement to two new tie-rail placements that follow the neck line of dairy cows when feeding and rising and to a tie-rail placement commonly found on Quebec dairy farms.

1.2 Objectives

1.2.1 Overall objectives

The main objective of this thesis is to provide a new recommendation for tie-rail placement based on the cow's neck line when they are feeding and rising to allow for improved ease of movement and yielding better outcome measures of welfare.

1.2.2 Specific objectives

1. To investigate the effect of new tie-rail placements that follow the cow's neck line compared to current recommendation in attempt to enhance dairy cow welfare such as ease of movement and injuries.

2. To investigate the effect of tie-rail placement commonly found on tie-stalls in Québec compared to current recommendation to inform farmers about the effect of a tie-rail placement commonly used as a way to enhance knowledge transfer between the scientific community and farmers.

Chapter 2. Literature Review

2.1 Importance of welfare

Dairy cow welfare has become an increasing concern for the general public. In a study by Cardoso et al. (2016) they asked the general public in regions of the U.S. what they would consider to be the ideal dairy farm and 90% of the respondents mentioned aspects of animal welfare and quality of life, for instance access to space and animal health. Another concept that respondents focused on was that of natural living, such as providing access to space and pasture (Cardoso et al., 2016). There are several views on animal welfare. Fraser et al. (1997) describes three well-established and major views of animal welfare. One view of animal welfare focuses on the biological functioning of the animal such as health, growth, and production. The second view focuses on the affective states of the animal such as pain and suffering. The third view focuses on animals being able to live in as natural conditions as possible, where animals are able to express their normal behaviour. Recent studies have found that the public are putting importance on the third view. For example, a study by Schuppli et al. (2014) surveying mainly participants from Canada and the U.S. asked participants "should dairy cows be provided access to pasture?" and found that the majority of all the respondents (81%) answered yes and 89% of the respondents who were not associated with the industry answered yes. Over half the participants that believed cows should have access to pasture reasoned that cows should have access to pasture because pasture access was more natural and better for dairy cow welfare. A survey in the U.S. showed that 46% of the respondents believed that it is important to allow animals to exhibit natural behaviours and have the opportunity to exercise outdoors (Prickett et al., 2010). Thus, surveys in North America have shown that the public consider animal welfare and letting animals exhibit natural behaviour important. Weary and von Keyserlingk (2017) discussed and reviewed how common practices on dairy farms such as indoor confinement are the target of public criticism and the authors give options to help relieve this criticism from the dairy industry. One of the options proposed by the authors was to conduct studies on animal welfare to help address those public concerns, and to develop and inform producers on systems that work well from the point of view of biological functioning, naturalness and affective state of the animals, following the three views of Fraser et al. (1997)'s definition of animal welfare.

Additionally, the Dairy Farmers of Canada are in the process of implementing a new national animal care assessment program through the proAction® initiative. The objective is to ensure that all Canadian dairy farms are meeting the standards for good cow welfare set by the

Canadian Code of Practice for the care and handling of dairy cattle (DFC - NFACC, 2009). A study conducted on 240 Canadian dairies by Vasseur et al. (2015) found that some recommendations of the Canadian Code of Practice are met on farm and some are not. For example, on tie-stall and free-stall farms recommendations for nutrition and feeding management were often met; however, few free-stall farms met recommendations for stall configuration and few tie-stall farms met recommendations for hock, knee and neck injuries. There is a common concern by the industry that meeting requirements for dairy cow welfare may be costly, for example barn renovations. However, a study by Robichaud et al. (2018) conducted on Canadian dairies concluded that meeting animal welfare standards through the proAction® initiative is unlikely to be an economic burden on the industry overall. The authors concluded that improving cow comfort and welfare could have the potential to financially benefit individual farms, depending on the costs associated with the improvements or changes needed to meet the specific recommendation or requirement.

2.2 Stall configuration is key in cow comfort

One aspect that can be investigated to improve dairy cow welfare is cow housing systems, and specifically for cows housed in indoor confinement, stall configuration. Previous studies have demonstrated that stall configuration affects dairy cow welfare. For instance, all aspects of stall configuration such as stall width, length, chain length, tie-rail/neck-rail height and forward position have an effect on outcome measures of welfare including lameness, injuries, cleanliness, as well as lying and rising behaviours (Zurbrigg et al., 2005; Rushen et al., 2007; Heyerhoff et al., 2014; Nash et al., 2016; Bouffard et al., 2017). In Canada there are two major types of stall designs: tie-stall (Figure 2.1) and free-stall (Figure 2.2) with 74.4% of cows housed in tie-stall barns (Canadian Dairy Information Centre, 2017). Yet, recommendations for tie-stall configuration are scarce (Anderson, 2014b) and studies to improve tie-stall configuration to optimize cow welfare are limited. This literature review will focus on one aspect of stall configuration: the front of the stall. This is also the topic of study for this thesis. This review will provide: **i)** a presentation of the role and recommendation for tie-rail placement, and its free-stall equivalent neck-rail and feed-rail placement, **ii)** an overview of the effects of tie-rail, neck-rail and feed-rail placement on dairy cow welfare outcome measures and **iii**) an introduction of different measures used to evaluate dairy cow welfare, including the ones used in the experiment (Chapter 4).

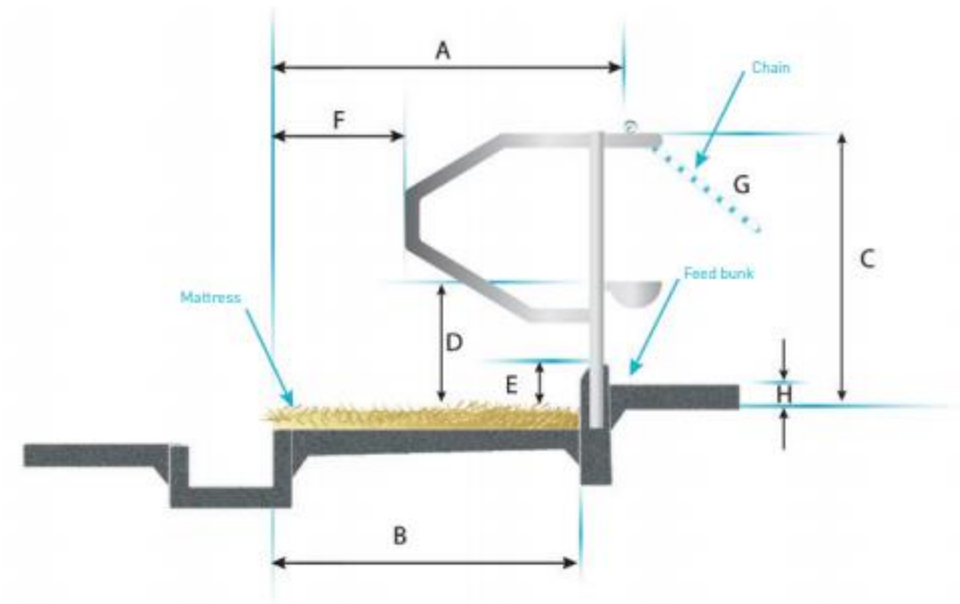

Figure 2.1 Example of Tie-stall configuration. (A) distance from tie-rail to the gutter; (B) stall length; (C) tie-rail height; (D) water bowl height; (E) brisket board height; (F) distance from the division to the gutter; (G) chain length; (H) height from the top of feed bunk to the top of the bedding. Image acquired from Valacta (2014).

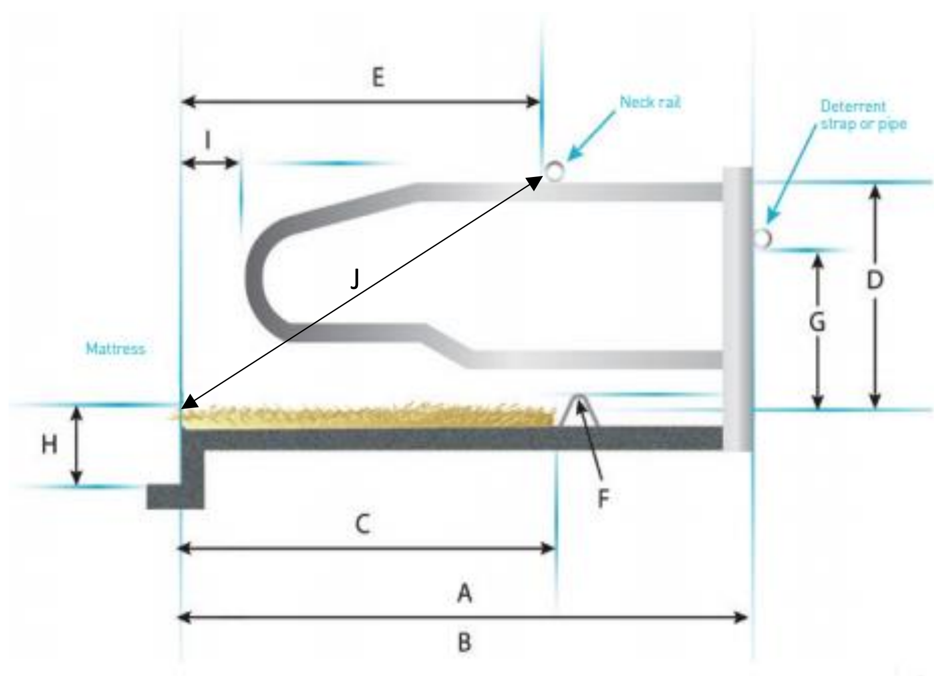

Figure 2.2 Example of free-stall configuration. (A & B) total length of stall; (C) platform length; (D) neck-rail height; (E) neck-rail distance; (F) brisket board height; (G) deterrent strap or pipe

height; (H) platform height; (I) space between the division and the alley; (J) diagonal distance from the end of stall to the neck rail. Image adapted from Valacta (2014).

2.3 Role and recommendation for tie-rail, neck-rail and feed-rail

Both tie-rail in the tie-stall and neck-rail in the free-stall act as a barrier at the front of the stall to help cows position themselves so that they do not leave the confines of their stall during lying and rising events (i.e. entering the manger area, another cow stall, or coming into contact with the front wall). Another function of the tie-rail and neck-rail is to facilitate stall cleanliness and manure management as it is positioned to allow cows to eliminate in the gutter or alley and not in the stall. Tie-rails have an additional function of separating cows from the manger area. This function is more akin to feed-rails in free-stall barns (Figure 2.3.)

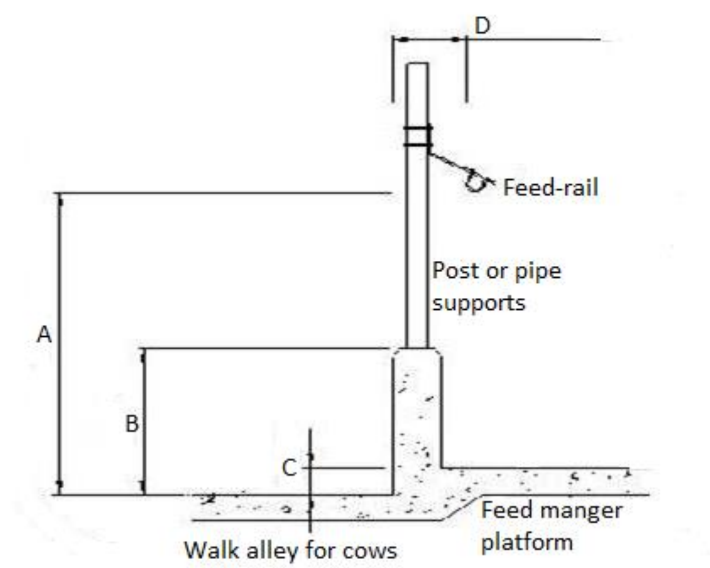

Figure 2.3 An example of post and rail feed barrier. (A) feed-rail height; (B) manger wall height; (C) feed manger height; (D) feed-rail distance. Image adapted from Anderson (2014) courtesy of H. House, OMAFRA

Because of their function (i.e., position the cow in her stall), most of the recommendations for tie-rail and neck-rail height and forward position are based on the cow's body dimensions, either height or body weight (which is extrapolated from both cow height and width). Recommendations for height (Figure 2.1(C) and Figure 2.2(D)) and forward positions (Figure 2.1(A) and Figure 2.2(E)) are similar in tie-rails and neck-rails, although tie-rail forward position in tie-stalls is recommended to be further from the cow compared to neck-rails in free-stalls (Table 2.1). In this review, we will be looking at the effect tie-rails, neck-rails, and feed-rails have on dairy cow welfare as they have similar functions. Studies often separate the effects of the rails based on height and forward position; therefore, we will be looking at the effects of tie-rail, neck-rail and feed-rail height and forward position separately. A few studies measure the diagonal position of the neck rail (Figure 2J); those studies will be considered separately as well and considered as combination effect of height and forward position.

Table 2.1 Recommendations for tie-rail and neck-rail height and forward positions

	Rail type and position			
Source of Recommendation	Tie-rail height (cm)	Tie-rail forward position (cm)	Neck-rail height (cm)	Neck-rail forward position (cm)
DFC - NFACC (2009)	111.8 – 121.9 for Holstein cows	-	For body weights (kg) 453.6 (111.8 cm), 544.3 (116.8 cm), 635.0 (121.9 cm), 725.7 (127 cm), and 816.5 (132.1 cm)	Distances from rear curb for body weights (kg) 453.6 (162.8 cm), 544.3 (167.6 cm), 635.0 (172.7 cm), 725.7 (177.8 cm), and 816.5 (182.9 cm)
Anderson (2014a) and Anderson (2014b)	0.80 x rump height	[1]20.3 – 30.5 forward from center of manger curb	0.83 x rump height	1.2 x rump height – 5.1 forward from alley curb
Valacta (2014)	0.7 – 0.8 x hip height	1.2 x hip height + 35.6 forward from gutter	0.83 x hip height	1.2 x hip height – 5.1 forward from alley curb

[1]For example 218.44 cm forward from the rear curb would allow cows with a rump height of about 147.32 – 152.4 cm to stand straight in the stall.

2.3.1 *Effect of rails on neck, hock and knee injuries and broken tails*

First, we will examine the effect tie-rails, neck-rails and feed rails have on cow injuries (Table 2.2). Studies on tie-rail height have found that when tie-rails are positioned at current recommendation (e.g. of median cow: 0.80 x 152.4 = 121.9 cm) or 10 cm higher there was an increased risk of neck injuries (Bouffard et al., 2017). Another study by Zurbrigg et al. (2005) found that mid-range tie-rail placements (99 - 114 cm) resulted in a greater percentage of neck injuries. Studies on feed rails contained similar findings that mid-range heights resulted in an increased risk of neck injuries and determined that feed rails should be positioned higher (Kielland et al., 2010; Heyerhoff et al., 2014). Although Kielland et al. (2010) recommended feed-rails be greater than 109 cm and Heyerhoff et al. (2014) recommended feed-rails be greater than 149 cm in height, this could be due to the fact that Kielland et al. (2010) measured mainly Norwegian Red dairy cows and Heyerhoff et al. (2014) measured mainly Holstein dairy cows, which are usually larger cows. The average shoulder height for Norwegian Red dairy cows is 133.6 ± 4.0 cm, whereas the average rump height for Holsteins is 150.6 ± 4.25 cm (Kielland et al., 2009; Bouffard et al., 2017). Additionally, Kielland et al. (2010) mentions that cows with higher shoulder heights require higher feed-rails. Potterton et al. (2011) found that neck rails with mid-range heights (111-115 cm) increased the risk of hair loss on hocks, and although it was not statistically significant, higher neck rails (124-136 cm) had a numerical decrease risk of hair loss on hocks. Additionally, Zurbrigg et al. (2005) showed that the prevalence of broken tails increased by 1% for every 2.5 cm decrease in height. Overall, most studies found that tie-rails, neck-rails and feed-rails at mid-range heights increased the risk of neck and hock injuries. Although, the definition of mid-range height was different for each study, most of the studies in free-stall suggested that increasing the neck-rails and feed-rails height decreased injuries, this was not the case for studies on tie-rail height in tie-stall.

For tie-rail forward position, Bouffard et al. (2017) found that when the tie-rail was at current recommendation (35 cm more than stall length) or 10 cm more, the risk of neck and knee injuries decreased. For the neck-rail it was found that increasing the forward position of the rail decreased the risk of hock injuries (Potterton et al., 2011; Heyerhoff et al., 2014). Conversely, Nash et al. (2016) found that the probability of hock injury was greater the further forward the tie-rail was positioned. Overall, increasing the forward position of tie-rails and neck-rails has the potential to decrease the risk of neck and knee injuries, however it is possible that increasing the forward position of tie-rails may result in an increase in hock injuries whereas the opposite was found for neck-rail position.

Table 2.2 Effect of rail position on neck, hock, knee injuries and broken tails

Variable	Stall type	Rail type	**Position**[1]	Measurement[2]	Comparison/ Association[3]	Significance	n	Reference
Neck injuries	Tie-stall	Tie-rail	**Height**	Low (71-96 cm) Mid (99-114 cm) High (116-132 cm)	Low and high tie-rails had 70% fewer neck lesions than midrange	(low) $P < 0.001$ (high) $P < 0.05$	317 farms 17,893 cows	Zurbrigg et al. (2005)
	Tie-stall	Tie-rail	**Height**	Current recommendation (0.8 x height of cow at rump) and/or 10 cm higher	OR[4] = 1.219	$P = 0.008$	100 farms 3,485 cows	Bouffard et al. (2017)
	Free-stall	Feed/top rail	**Height**	(1) < 98 cm (2) 98-109 cm (3) > 109 cm	(1) OR = 0.65 (2) OR = 3.52 (3) OR = 1.00	(1) P = NS[5] (2) $P < 0.001$ (3) -	232 farms	Kielland et al. (2010)
	Free-stall	Feed rail	**Height**	(1) ≤ 127.5 cm (2) 127.6-139.9 cm (3) 140-148.9 cm (4) ≥ 149 cm	(1) prevalence = 13; OR = 43.82 (2) prevalence = 21; OR = 76.71 (3) prevalence = 11; OR = 4.01 (4) prevalence = 1	(1) $P < 0.001$ (2) $P < 0.001$ (3) $P = 0.091$ (4) -	87 farms 40 cows per farm	Heyerhoff et al. (2014)
	Tie-stall	Tie-rail	**Forward**	Current recommendation (35 cm more than stall length, from the back of stall) and/or 10 cm more	Odds ratio = 0.582	$P < 0.001$	100 farms 3,485 cows	Bouffard et al. (2017)
Hock Injuries	Free-stall	Neck-rail	**Height**	(1) 0.91-1.10 m (2) 1.11-1.15 m (3) 1.16-1.23 m (4) 1.24-1.36 m	(1) reference (2) OR = 2.80 (3) OR = 1.67 (4) OR = 0.61	(1) reference (2) $P < 0.05$ (3) NS (4) NS	63 farms 50 cows per farm	Potterton et al. (2011)
	Free-stall	Neck-rail	**Forward**	Neck rail distance from rear of stall curb: per 10 cm increase	OR = 0.74	$P < 0.001$	87 farms 40 cows per farm	Heyerhoff et al. (2014)
	Free-stall	Neck-rail	**Forward**	Distance from curb: (1) 1.88 – 1.98 m (2) 1.99 – 2.07 m (3) 2.08 – 2.14 m (4) 2.15 – 2.37 m	(1) reference (2) OR = 0.49 (3) OR = 0.14 (4) OR = 0.09	(1) reference (2) NS (3) $P < 0.05$ (4) $P < 0.05$	63 farms 50 cows per farm	Potterton et al. (2011)
	Tie-stall	Tie-rail	**Forward**	Per cm increase in tie-rail forward position	Coefficient = 0.0036 ± 0.0066	$P = 0.003$	100 farms 40 cows per farm	Nash et al. (2016)
Knee injuries	Tie-stall	Tie-rail	**Forward**	Current recommendation (35 cm more than stall length, from the back of stall) and/or 10 cm more	OR = 0.83	$P < 0.001$	100 farms 3,485 cows	Bouffard et al. (2017)
Broken tails	Tie-stall	Tie-rail	**Height**	For each 2.5cm decrease in height	Prevalence increase by 1%	$P < 0.001$	317 farms 17,893 cows	Zurbrigg et al. (2005)

[1]Indicates which position of the rail that is being considered, either the height, forward, or diagonal position

[2]The measurements of each position observed or tested per study

[3]Demonstrates tie-rails association with the variable in epidemiological studies and compares the tie-rails tested in experimental studies.

[4]OR = odd ratio

[5]NS = not significant with a P-value greater than 0.05

2.3.2 *Effect of rails on lameness and hoof health*

The effect of tie-rail and neck-rail on lameness will now be considered (Table 2.3). Bouffard et al. (2017) found that when tie-rail height met current recommendation (e.g. of median cow: 0.80 x 152.4 = 121.9 cm) or 10 cm higher, the risk of lameness increased. Contrarily, a study on free-stalls by Solano et al. (2015) found that when the neck-rails were positioned higher (max. = 117 ± 8 cm) the prevalence of lameness was lower (0-30%). These contradictory results may have been found due to the fact that the maximum heights observed by Solano et al. (2015) for free-stall neck-rail heights were likely lower than the current recommendation height or 10 cm observed by Bouffard et al. (2017). This suggests that higher is only better until a point, and current recommendation for tie-rail height may be too high. As a result, tie-stall needs may be different from free-stall needs in terms of rail height.

The forward position of tie-rails and neck rails have both been shown to have a similar effect on lameness: increasing the forward position resulted in a decreased risk/prevalence of lameness (Bernardi et al., 2009; Chapinal et al., 2013; Solano et al., 2015; Bouffard et al., 2017). Bernardi et al. (2009) found that increasing the forward position of the neck-rail reduced the number of new cases of hoof sole lesions and digital dermatitis that developed during the study. Similar findings were observed when looking at the diagonal distance of neck-rails; the risk/prevalence of lameness decreased when the diagonal distance was longer (Dippel et al., 2009; Rouha-Mulleder et al., 2009). Overall, increasing the tie-rail and neck-rails forward position may reduce lameness on farm.

Table 2.3 Effect of rail positions on lameness and hoof health

Variable	Stall type	Rail type	**Position**[1]	Measurement[2]	Association/ Comparison[3]	Significance	n	Reference
In stall lameness scoring (Leach et al., 2009)	Tie-stall	Tie-rail	**Height**	Current recommendation (0.8 x height of cow at rump) and/or 10 cm higher	OR[4] = 1.105	$P < 0.078$	100 farms 3,485 cows	Bouffard et al. (2017)
	Tie-stall	Tie-rail	**Forward**	Current recommendation (35 cm more than stall length, from the back of stall) and/or 10 cm more	OR = 0.760	$P < 0.001$	100 farms 3,485 cows	Bouffard et al. (2017)
Locomotion scoring (NRS: 1-5 system; ≥ 3 is lame)	Free-stall	Neck-rail	**Height**	(1) 117 ± 8 cm (2) 116 ± 8 cm	Prevalence of lameness (%): (1) 0-30 (2) ≥ 30	-	141 farms 40 cows per farm	Solano et al. (2015)
	Free-stall	Neck- rail	**Forward**	Distance from rear curb: (1) 130 cm (2) 190 cm	Newly lame: (1) 11 (2) 2	$P = 0.01$	32 cows	Bernardi et al. (2009)
	Free-stall	Neck-rail	**Forward**	Horizontal distance from rear curb: for 1-cm increase	Decreased lameness (OR = 0.97)	Confidence Interval = 0.95-0.99	79 farms (measured 1 high producing pen/farm)	Chapinal et al. (2013)
	Free-stall	Neck-rail	**Forward**	Distance from rear curb: (1) 173 ± 9 cm (2) 168 ± 9 cm (3) 167 ± 10 cm	Prevalence of lameness (%): (1) ≤ 10 (2) 10 - 30 (3) ≥ 30	-	141 farms 40 cows per farm	Solano et al. (2015)
	Free-stall	Neck-rail	**Diagonal**	Diagonal distance between the neck rail and curb too short when diagonal < square root of $[(0.92 \times \text{rump diagonal})^2 + (0.75 \times \text{height of withers})^2]$ cm	Risk of lameness increased when too short (OR = 0.78)	P = 0.017	103 farms (herd size: 24-145 cows)	Dippel et al. (2009)
	Cubicle loose-housed	Neck-rail	**Diagonal**	Diagonal distance from the end of cubicles to neck rail: (1) shorter = 1.8 - 2.1 m (2) longer = 1.9 - 2.1 m	(1) shorter = prevalence of lameness ≥ 36% (2) longer = Prevalence of lameness ≤ 36%	-	80 farms (herd size: 21-60 cows)	Rouha-Mulleder et al. (2009)
Sole lesions	Free-stall	Neck-rail	**Forward**	Distance from rear curb: (1) 130 cm (2) 190 cm	(1) 15 new cases (2) 1 new case	P < 0.001	32 cows	Bernardi et al. (2009)
Digital dermatitis	Free-stall	Neck-rail	**Forward**	Distance from rear curb: (1) 130 cm (2) 190 cm	(1) 6 new cases (2) 3 new cases	P > 0.05	32 cows	Bernardi et al. (2009)

[1]Indicates which position of the rail that is being considered, either the height, forward, or diagonal position

[2]The measurements of each position observed or tested per study

[3]Demonstrates tie-rails association with the variable in epidemiological studies and compares the tie-rails tested in experimental studies.

[4]OR = odd ratio

2.3.3 *Effect of rails on standing and lying behaviours*

The effect of tie-rail and neck-rail on standing and lying behaviours will now be considered (Table 2.4 and 2.5). Studies have found that neck-rail height in free-stall barns did not have a significant effect on amount of time cows spend standing with only their front two hooves in the stall (Gaworski et al., 2003; Tucker et al., 2009). In a free-stall study by Tucker et al. (2005), they found that when neck-rail height was increased (max. = 127 cm) or neck-rail was absent cows spent more time standing with all four hooves in the stall. Contrarily, Gaworski et al. (2003) found that larger stalls with a higher tie-rail position (max. = 125 cm) did not have an effect on the amount of time cows spent with all four hooves in the stall. This may have occurred because overall the stall size was larger in the study performed in Tucker et al. (2005) compared to Gaworski et al. (2003), resulting in cows spending more time with all four hooves in the stall for the Tucker et al. (2005) study. Also, as expected when neck-rail was absent, cows spent even more time with all four hooves in the stall (Tucker et al., 2005). For total time spent lying Bouffard et al. (2017) found that cows spent less time lying when housed in stalls with tie-rail heights at current recommendation or 10 cm higher. However, studies on free-stalls found that neck-rail height and even the absent of a neck-rail did not have an effect on lying time (Gaworski et al., 2003; Tucker et al., 2005). This difference could be due to the fact that tie-stall cows are tied and thus spend majority of their time in their stall, creating a different requirement for rail height. Cows may be restricted by the chain in terms of space and ease of movement; if the tie-rail is too high and the chain is too short, this could create pressure on the cows neck when lying down; or restrict cows from performing certain lying postures such as resting head on flank. Bouffard et al. (2017) also found that the number of lying bouts decreased when tie-rail height was at current recommendation or 10 cm, whereas Tucker et al. (2005) found that neck-rail height did not have an effect on number of lying bouts. Tucker et al. (2005) also found that neck-rail height did not have an effect on the duration of lying bouts. Overall, in free-stalls increasing neck-rail height may allow cows to spend more time standing fully in their stall. Nonetheless, neck-rail height was not found to affect lying behaviours, but increasing tie-rail height in tie-stalls to meet current recommendation had a negative effect on lying behaviours (Bouffard et al., 2017). This suggests that requirements for tie-rail and neck-rail height may be different.

In free-stall studies, it was consistently found that increasing neck-rail forward position decreased the amount of time cows spent standing with only their two front hooves in the stall (Tucker et al., 2005; Bernardi et al., 2009; Fregonesi et al., 2009). Additionally, cows spent more time standing with all four hooves in the stall when neck-rail forward position was increased, but neck-rail forward position did not have an effect on the total time spent standing in the stall (Tucker et al., 2005; Bernardi et al., 2009; Fregonesi et al., 2009). Studies have also found that tie-rail and neck-rail forward position did not have a significant effect on the lying time of tie-stall or free-stall housed cows (Tucker et al., 2005; Bernardi et al., 2009; Fregonesi et al., 2009; Bouffard et al., 2017). A study on tie-stalls by Bouffard et al. (2017) and a study on free-stalls by Bernardi et al. (2009) found that increasing the tie-rail (met current recommendation or 10 cm more) or neck-rail (max. = 130 cm) forward position increased the number of lying bouts. However, Tucker et al. (2005) found that the neck-rail forward positions did not have an effect on number of lying bouts for cows housed in a free-stall barn. This could be because the minimum distance (min. = 140 cm) tested in Tucker et al. (2005) was 10 cm greater than the minimum distance (min. = 130 cm) tested in Bernardi et al. (2009); therefore, the minimum distance tested by Tucker et al. (2005) may not have been close enough to the stall curb to see a difference. Tucker et al. (2005) also found that neck-rail forward position did not have an effect on the duration of lying bouts. Overall studies suggest that advancing the forward position of the neck-rail increases the amount of time cows spent standing in stall with all 4 hooves. Advancing the forward position of the tie-rail or neck-rail may also increase the number of lying bouts, suggesting that cows may feel more comfortable at changing positions between lying and rising in stalls with tie-rails or neck-rails further from the rear curb of the stall.

Table 2.4 Effect of rail position on lying behaviours

Variable	Stall type	Rail type	**Position**[1]	Measurement[2]	Association/ Comparison[3]	Significance	n	Reference
Lying time	Tie-stall	Tie-rail	**Height**	Current recommendation (0.8 x height of cow at rump) and/or 10 cm higher	Coefficient = -0.114 ± 0.054	$P = 0.034$	100 farms 3,485 cows	Bouffard et al. (2017)
	Free-stall	Neck-rail	**Height**	(1) Recommendations: neck rail height = 112.5 cm, stall width = 110 cm, and bedding = 40 cm of sand (2) Larger stalls: neck rail height = 125 cm, stall width = 117.5 cm, and bedding = 4-5 cm of sand on geotextile mattress	% of time/d: (1) 55.4 ± 0.44 (2) 55.7 ± 0.44	$P = 0.616$	48 cows	Gaworski et al. (2003)
	Free-stall	Neck-rail	**Height**	Height: (1) 102 cm (2) 114 cm (3) 127 cm (4) No neck rail	h/24 h: (1) 14.8 ± 0.54 (2) 13.9 ± 0.71 (3) 14.3 ± 0.64 (4) 13.7 ± 0.89	NS	10 cows	Tucker et al. (2005)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 190 cm	h/d: (1) 12.3 ± 0.6 (2) 12.3 ± 0.6	NS	32 cows	Bernardi et al. (2009)
	Tie-stall	Tie-rail	**Forward**	Current recommendation (35 cm more than stall length, from the back of stall) and/or 10 cm more	Coefficient = 0.067 ± 0.045	$P = 0.072$	100 farms 3,485 cows	Bouffard et al. (2017)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 145 cm (3) 160 cm (4) 175 cm (5) 190 cm	Overall average (h/d): 12.0 ± 0.4	NS	30 cows	Fregonesi et al. (2009)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 140 cm (2) 175 cm (3) 233 cm	h/24 h: (1) 8.7 ± 0.86 (2) 8.8 ± 0.81 (3) 9.1 ± 0.76	NS	12 cows	Tucker et al. (2005)
Number of lying bouts	Tie-stall	Tie-rail	**Height**	Current recommendation (0.8 x height of cow at rump) and/or 10 cm higher	Coefficient = -0.212 ± 0.086	$P = 0.034$	100 farms 3,485 cows	Bouffard et al. (2017)
	Free-stall	Neck-rail	**Height**	Height: (1) 102 cm (2) 114 cm (3) 127 cm (4) No neck rail	No./24 h: (1) 8.8 ± 0.89 (2) 7.7 ± 1.02 (3) 9.7 ± 1.27 (4) 9.7 ± 1.49	NS	10 cows	Tucker et al. (2005)
	Tie-stall	Tie-rail	**Forward**	Current recommendation (35 cm more than stall length, from the back of stall) and/or 10 cm more	Coefficient = 0.067 ± 0.045	$P = 0.027$	100 farms 3,485 cows	Bouffard et al. (2017)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 190 cm	Bouts/d: (1) 9.6 ± 0.2 (2) 10.4 ± 0.2	$P < 0.01$	32 cows	Bernardi et al. (2009)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 140 cm (2) 175 cm	No./24 h: (1) 12.1 ± 0.64 (2) 12.3 ± 0.71	NS	12 cows	Tucker et al. (2005)

				(3) 233 cm	(3) 12.0 ± 0.69			
Duration of lying bouts	Free-stall	Neck-rail	**Height**	Height: (1) 102 cm (2) 114 cm (3) 127 cm (4) No neck rail	h/bout : (1) 1.8 ± 0.16 (2) 2.0 ± 0.17 (3) 1.7 ± 0.16 (4) 1.6 ± 0.19	NS	10 cows	Tucker et al. (2005)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 140 cm (2) 175 cm (3) 233 cm	h/bout : (1) 1.5 ± 0.15 (2) 1.6 ± 0.18 (3) 1.4 ± 0.12	NS	12 cows	Tucker et al. (2005)

[1]Indicates which position of the rail that is being considered, either the height, forward, or diagonal position

[2]The measurements of each position observed or tested per study

[3]Demonstrates tie-rails association with the variable in epidemiological studies and compares the tie-rails tested in experimental studies.

[4]NS = not significant with a *P*-value greater than 0.05

[5]When there is only one p-value for comparing multiple measurements a Page's test was used to test for a linear trend between the ordered variables (e.g. lowest to highest)

Table 2.5 Effect of rail position on standing behaviours

Variable	Stall type	Rail type	**Position**[1]	Measurement[2]	Association/ Comparison[3]	Significance	n	Reference
Standing with front 2 hooves in the stall	Free-stall	Neck-rail	**Height**	Height: (1) 102 cm (2) 114 cm (3) 127 cm (4) No neck rail	Min/2 h: (1) 26 ± 6.9 (2) 27 ± 13.9 (3) 26 ± 9.7 (4) 40 ± 22	NS	10 cows	Tucker et al. (2005)
	Free-stall	Neck-rail	**Height**	(1) Recommendations: neck rail height = 112.5 cm, stall width = 110 cm, and bedding = 40 cm of sand (2) Larger stalls: neck rail height = 125 cm, stall width = 117.5 cm, and bedding = 4-5 cm of sand on geotextile mattress	% of time/d: (1) 7.6 ± 0.34 (2) 7.5 ± 0.34	NS	48 cows	Gaworski et al. (2003)
	Free-stall	Neck-rail	**Forward**	Distance from rear curb: (1) 130 cm (2) 190 cm	h/d: (1) 2.2 ± 0.26 (2) 1.7 ± 0.27	$P < 0.01$	30 cows	Fregonesi et al. (2009)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 140 cm (2) 175 cm (3) 233 cm	Min/ 24 h: (1) 79 ± 20.0 (2) 64 ± 24.1 (3) 53 ± 17.6	$P < 0.01$[5]	12 cows	Tucker et al. (2005)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 190 cm	Min/d: (1) 49 ± 6 (2) 33 ± 6	$P < 0.02$	32 cows	Bernardi et al. (2009)
Time standing with 4 hooves in stall	Free-stall	Neck-rail	**Height**	Height: (1) 102 cm (2) 114 cm (3) 127 cm (4) No neck rail	Min/ 24 h: (1) 22 ± 6.1 (2) 21 ± 6.9 (3) 40 ± 9.5 (4) 83 ± 32	$P < 0.01$	10 cows	Tucker et al. (2005)
	Free-stall	Neck-rail	**Height**	(1) Recommendations: neck rail height = 112.5 cm, stall width = 110 cm, and bedding = 40 cm of sand (2) Larger stalls: neck rail height = 125 cm, stall width = 117.5 cm, and bedding = 4-5 cm of sand on geotextile mattress	% of time/d: (1) 7.6 ± 0.34 (2) 7.5 ± 0.34	$P = 0.762$	48 cows	Gaworski et al. (2003)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 190 cm	h/d: (1) 0.0 ± 0.02 (2) 0.6 ± 0.07	$P < 0.001$	30 cows	Fregonesi et al. (2009)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 140 cm (2) 175 cm (3) 233 cm	Min/ 24 h: (1) 11 ± 3.5 (2) 43 ± 10.4 (3) 86 ± 33.9	$P < 0.001$	12 cows	Tucker et al. (2005)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 190 cm	Min/d (1) 1 ± 3 (2) 27 ± 3	$P < 0.001$	32 cows	Bernardi et al. (2009)
Total time standing in stall	Free-stall	Neck-rail	**Height**	Height: (1) 102 cm (2) 114 cm (3) 127 cm (4) No neck rail	Min/24 h: (1) 48 ± 11.8 (2) 48 ± 13.6 (3) 66 ± 12.5 (4) 123 ± 34.2	$P < 0.01$	10 cows	Tucker et al. (2005)

Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 140 cm (2) 175 cm (3) 233 cm	Min/ 24 h: (1) 89 ± 19.4 (2) 107 ± 29.7 (3) 139 ± 40.0	NS	12 cows	Tucker et al. (2005)

[1]Indicates which position of the rail that is being considered, either the height, forward, or diagonal position

[2]The measurements of each position observed or tested per study

[3]Demonstrates tie-rails association with the variable in epidemiological studies and compares the tie-rails tested in experimental studies.

[4]NS = not significant with a *P*-value greater than 0.05

[5]When there is only one p-value for comparing multiple measurements a Page's test was used to test for a linear trend between the ordered variables (e.g. lowest to highest)

2.3.4 *Effect of rails on cow and stall cleanliness*

The effect of tie-rails and neck-rails on dairy cow and stall cleanliness will now be considered (Table 2.6). A study by Zurbrigg et al. (2005) on tie-stall barns found that with every 2.5 cm increase in tie-rail height, the prevalence of clean udders increased by 0.2%. However, another study by Tucker et al. (2005) found that neck-rail height did not have an effect on total defecation and urination that come in contact with the stall, regardless of whether the cow was standing with the front two hooves in the stall, standing with all four hooves in the stall, or while lying in the stall. Thus, tie-rails in tie-stalls may provide cows with a visual barrier when positioned higher compared to neck-rails, allowing the cow to position herself according to stall length, and limiting defecation and urination in the stall. On the other hand, tie-rails that were positioned higher on farms may have also been positioned closer to the rear curb of the stall, limiting stall length (and reducing the cow's to defecate and urinate inside the stall). Other confounding factors such as different management strategies between farms (i.e., frequency of stall cleaning, quantity of bedding, etc.) may have explained these results.

A study on tie-stalls by Bouffard et al. (2017) found that when tie-rail forward positions met current recommendations or 10 cm forward, there was an increased risk of dirty udders. These findings are similar to a study on free-stalls by Fregonesi et al. (2009), who found that increasing neck-rail forward position (max. = 190 cm) resulted in an increase of dirty udders. Conversely, a study by Bernardi et al. (2009) found that neck-rail forward position did not significantly affect udder cleanliness. However, there was a numerical increase in dirty udders when neck-rail forward position was increased (max. = 190 cm). Bernardi et al. (2009) also found that teats took more time to clean when the neck-rail forward position was increased. For stall cleanliness Fregonesi et al. (2009) found that total defecations that came in contact with the stall's surface was greater when neck-rail forward position was increased (max. = 190 cm), whereas Tucker et al. (2005) found that tie-rail forward position (max. = 223 cm) did not have an effect on total defecations that contacted the stall's surface. Fregonesi et al. (2009) also found that increasing the neck-rail forward position increased the instances of defecation coming in contact with the stall's surface while the cow was lying. Tucker et al. (2005) found that neck-rail forward position did not have an effect on defecations that came in contact with the stall's surface while the cow was lying. Both Fregonesi et al. (2009) and Bernardi et al. (2009) found that when neck-rail forward position was increased, defecations came in contact with the stall's surface more often while cows were standing with all four hooves in the stall. However, they also found that neck-rail forward position did not have an effect on defecations coming in contact with the stall's surface while the cows were standing with only their two front hooves in the stall (Tucker et al., 2005; Fregonesi et al., 2009). Tucker et al. (2005) found that neck-rail forward position did not have an effect on urine that came in contact with the stall's surface whether the cow was standing with all four hooves in the stall, standing with only their two front hooves in the stall, or lying in the stall. Fregonesi et al. (2009) also found that neck-rail forward position did not have an effect on urine coming in contact with the stall's surface when the cow was standing with only two hooves in the stall or lying. However, Fregonesi et al. (2009) found that increasing neck-rail forward position did increase the number of times urine came in contact with the stall's surface when the cow was standing with all four hooves in the stall and the overall number of times urine came in contact with the stall's surface. Additionally, Fregonesi et al. (2009) found that the time required to clean the stalls was greater for stalls with neck-rails positioned further from the rear curb. Bernardi et al. (2009) also found that increasing neck-rails forward position reduced stall cleanliness. Similar results were found by Ruud et al. (2011), who found that neck-rails with diagonals ≤ 1.96 m lowered the risk of stall contamination. Overall, studies suggest that increasing tie-rail and neck-rail forward position reduces cow and stall cleanliness.

Table 2.6 Effect of rail position on cow and stall cleanliness and associated elimination behaviours

Variable	Stall type	Rail type	**Position**[1]	Measurement[2]	Association/ Comparison[3]	Significance	n	Reference
Udder cleanliness	Tie-stall	Tie-rail	**Height**	With a 2.5cm increase in tie-rail height	Increased the prevalence of clean udders by 0.2%	$P < 0.05$	317 farms, 17,893 cows	Zurbrigg et al. (2005)
	Tie-stall	Tie-rail	**Forward**	Current recommendation (35 cm more than stall length, from the back of stall) and/or 10 cm more	Dirty udder: OR[4] = 1.202	$P = 0.032$	100 farms 3,485 cows	Bouffard et al. (2017)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 190 cm	Udder hygiene score: (1) 1.2 ± 0.07 (2) 1.4 ± 0.08	$P < 0.05$	30 cows	Fregonesi et al. (2009)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 190 cm	Udder cleanliness score: (1) 2.0 (2) 2.5	$P = 0.10$	32 cows	Bernardi et al. (2009)
Teat cleaning time	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 190 cm	Min: (1) 7.0 ± 0.2 (2) 8.3 ± 0.2	$P < 0.001$	32 cows	Bernardi et al. (2009)
Defecations that contacted stall while standing with front 2 hooves in stall	Free-stall	Neck-rail	**Height**	(1) 102 cm (2) 114 cm (3) 127 cm (4) No neck rail	Events/ 24 h: (1) 0.0 ± 0.00 (2) 0.0 ± 0.00 (3) 0.0 ± 0.00 (4) 0.0 ± 0.00	NS[5]	10 cows	Tucker et al. (2005)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 145 cm (3) 160 cm (4) 175 cm (5) 190 cm	Events/24 h: (1) 0.0 ± 0.00 (2) 0.0 ± 0.00 (3) 0.0 ± 0.00 (4) 0.0 ± 0.00 (5) 0.0 ± 0.00	-	30 cows	Fregonesi et al. (2009)
Defecations that contacted stall while standing with all 4 hooves in stall	Free-stall	Neck-rail	**Height**	(1) 102 cm (2) 114 cm (3) 127 cm (4) No neck rail	Events/ 24 h: (1) 0.6 ± 0.30 (2) 0.2 ± 0.27 (3) 0.6 ± 0.10 (4) 0.9 ± 0.37	NS	10 cows	Tucker et al. (2005)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 145 cm (3) 160 cm (4) 175 cm (5) 190 cm	Events/ 24 h: (1) 0.0 ± 0.01 (2) 0.0 ± 0.01 (3) 0.2 ± 0.01 (4) 0.5 ± 0.05 (5) 0.5 ± 0.06	$P < 0.001$[6]	30 cows	Fregonesi et al. (2009)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 140 cm (2) 175 cm (3) 233 cm	Events/ 24 h: (1) 0.0 ± 0.0 (2) 0.2 ± 0.05 (3) 0.1 ± 0.04	$P \leq 0.05$	12 cows	Tucker et al. (2005)
Defecations that contacted stall while lying in stall	Free-stall	Neck-rail	**Height**	(1) 102 cm (2) 114 cm (3) 127 cm (4) No neck rail	Events/ 24 h: (1) 0.3 ± 0.50 (2) 0.5 ± 0.20 (3) 0.1 ± 0.43 (4) 0.7 ± 0.60	NS	10 cows	Tucker et al. (2005)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb:	Events/24 h:	$P < 0.001$	30 cows	Fregonesi et al. (2009)

				(1) 130 cm (2) 145 cm (3) 160 cm (4) 175 cm (5) 190 cm	(1) 0.1 ± 0.02 (2) 0.1 ± 0.02 (3) 0.2 ± 0.02 (4) 0.3 ± 0.04 (5) 0.4 ± 0.06			
Defecations that contacted the stall	Free-stall	Neck-rail	**Height**	(1) 102 cm (2) 114 cm (3) 127 cm (4) No neck rail	Events/ 24 h: (1) 0.9 ± 0.60 (2) 0.7 ± 0.30 (3) 0.7 ± 0.42 (4) 1.6 ± 0.60	NS	10 cows	Tucker et al. (2005)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 145 cm (3) 160 cm (4) 175 cm (5) 190 cm	Events/24 h: (1) 0.1 ± 0.02 (2) 0.2 ± 0.03 (3) 0.4 ± 0.03 (4) 0.7 ± 0.07 (5) 0.9 ± 0.06	*P* < 0.001	30 cows	Fregonesi et al. (2009)
	Free-stall	Neck-rail	**Diagonal**	Diagonal distance: equal to or less than 1.96 m	Lower risk of faeces contamination	-	224 farms	Ruud et al. (2011)
	Free-stall	Upper head-rail	**Height**	(1) ≤ 0.70 m (2) > 0.70 m (3) not present	OR: (1) 1.48 (2) 1.00 (3) 1.35	(1) *P* < 0.05 (2) - (3) *P = 0.077*	224 farms	Ruud et al. (2011)
Urinations that contacted stall while standing with front 2 hooves in stall	Free-stall	Neck-rail	**Height**	(1) 102 cm (2) 114 cm (3) 127 cm (4) No neck rail	Events/24 h: (1) 0.0 ± 0.00 (2) 0.0 ± 0.00 (3) 0.0 ± 0.00 (4) 0.0 ± 0.00	NS	10 cows	Tucker et al. (2005)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 145 cm (3) 160 cm (4) 175 cm (5) 190 cm	Events/24 h: (1) 0.0 ± 0.00 (2) 0.0 ± 0.00 (3) 0.0 ± 0.00 (4) 0.0 ± 0.00 (5) 0.0 ± 0.01	-	30 cows	Fregonesi et al. (2009)
Urinations that contacted stall while standing with all 4 hooves in stall	Free-stall	Neck-rail	**Height**	(1) 102 cm (2) 114 cm (3) 127 cm (4) No neck rail	Events/24 h: (1) 0.0 ± 0.00 (2) 0.0 ± 0.00 (3) 0.1 ± 0.10 (4) 0.2 ± 0.20	NS	10 cows	Tucker et al. (2005)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 145 cm (3) 160 cm (4) 175 cm (5) 190 cm	Events/24 h: (1) 0.0 ± 0.00 (2) 0.0 ± 0.00 (3) 0.1 ± 0.02 (4) 0.1 ± 0.01 (5) 0.2 ± 0.04	*P* < 0.001	30 cows	Fregonesi et al. (2009)
Urinations that contacted stall while lying in stall	Free-stall	Neck-rail	**Height**	(1) 102 cm (2) 114 cm (3) 127 cm (4) No neck rail	Events/24 h: (1) 0.0 ± 0.00 (2) 0.0 ± 0.00 (3) 0.0 ± 0.00 (4) 0.0 ± 0.00	NS	10 cows	Tucker et al. (2005)

	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 145 cm (3) 160 cm (4) 175 cm (5) 190 cm	Events/24 h: (1) 0.0 ± 0.00 (2) 0.0 ± 0.00 (3) 0.0 ± 0.00 (4) 0.0 ± 0.00 (5) 0.0 ± 0.00	-	30 cows	Fregonesi et al. (2009)
Urinations that contacted the stall	Free-stall	Neck-rail	**Height**	(1) 102 cm (2) 114 cm (3) 127 cm (4) No neck rail	Events/24 h: (1) 0.0 ± 0.00 (2) 0.0 ± 0.00 (3) 0.1 ± 0.10 (4) 0.2 ± 0.20	NS	10 cows	Tucker et al. (2005)
	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 145 cm (3) 160 cm (4) 175 cm (5) 190 cm	Events/24 h: (1) 0.0 ± 0.00 (2) 0.0 ± 0.00 (3) 0.1 ± 0.02 (4) 0.1 ± 0.01 (5) 0.2 ± 0.04	$P < 0.001$	30 cows	Fregonesi et al. (2009)
Stall cleanliness	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 190 cm	Stall cleanliness score: (1) 0.4 ± 0.2 (2) 3.7 ± 0.2	$P < 0.001$	32 cows	Bernardi et al. (2009)
Time required to clean stall	Free-stall	Neck-rail	**Forward**	Distance from the rear curb: (1) 130 cm (2) 190 cm	Min/d : (1) 0.4 ± 0.16 (2) 1.6 ± 0.35	$P < 0.001$	30 cows	Fregonesi et al. (2009)

[1]Indicates which position of the rail that is being considered, either the height, forward, or diagonal position

[2] The measurements of each position observed or tested per study

[3]Demonstrates the rails association with the variable in epidemiological studies or compares the rails tested in experimental studies.

[4]OR = odd ratio

[5] NS = not significant with a *P*-value greater than 0.05

[6]When there is only one p-value for comparing multiple measurements a Page's test was used to test for a linear trend between the ordered variables (e.g. lowest to highest)

2.3.5 *Summary of tie-rail, neck-rail and feed-rail effects on dairy cow welfare*

In summary, most studies found that tie-rails, neck-rails and feed-rails at mid-range heights increased the risk of neck and hock injuries (Zurbrigg et al., 2005; Kielland et al., 2010; Potterton et al., 2011; Heyerhoff et al., 2014), except for a study on tie-stall barns by Bouffard et al. (2017), who found that when tie-rails met current recommendation for height or 10 cm higher the risk of neck injuries increased. Conflicting results were also found for the effect of neck-rail and tie-rail heights on lameness, lying behaviours and cleanliness. For instance, increasing neck-rail height in free-stalls was found to reduce the prevalence of lameness, and had no effect on lying behaviours and cleanliness (Gaworski et al., 2003; Tucker et al., 2005; Solano et al., 2015). For tie-stalls, increasing tie-rail height or tie-rails at current recommendation or higher increased the risk of lameness, reduced lying time and number of lying bouts, and increased the prevalence of clean udders (Zurbrigg et al., 2005; Bouffard et al., 2017). These results suggest that increasing tie-rail and/or neck-rail height is only good to a point or the height requirement for tie-rails in tie-stall barns needs to be different from the height requirement for neck-rails in free-stall barns. On tie-stalls, cows are attached to the tie-rail in which creates a different interaction between the cow and the rail than in free-stalls. It was also found in free-stall barns that neck-rail height may allow cows to stand with all four hooves in the stall more often, which is an indicator that cows feel less restricted at the front of the stall, allowing cows to stand fully in their stall. It would be interesting to see if the same results can be found in tie-stall barns.

More consistent results were found for the effect of tie-rail and neck-rail forward positions on injuries, lameness, lying and standing behaviours, and cleanliness, with the exception one study by Nash et al. (2016), who found that increasing tie-rail forward position increased the probability of hock injury. Results of the other studies presented above found that increasing the forward position of tie-rails and neck-rails may decrease the risk/prevalence of neck, hock and knee injuries, sole lesions, digital dermatitis, lameness, increase the number of lying bouts, and reduce cow and stall cleanliness. Additionally, studies on free-stalls found that increasing the neck-rail forward position increases the amount of time cows are standing fully in their stall with all four hooves. It would be interesting to see if the same results could be found for tie-rail forward position in tie-stalls.

In conclusion, **i.** there are conflicting results for proper neck-rail and tie-rail height and forward position, **ii.** effects of other stall dimensions and management practices and their interaction with rail placement could not be isolated in epidemiological studies, and **iii.** some welfare outcome measures were not considered in previous studies, such as lying-down and rising behaviours, making it difficult to evaluate the validity of recommendations for tie-rail placement. Conflicting results for both height and forward positions suggest that combining both positions of tie-rail may be a good idea in order to find the ideal tie-rail placement recommendation. An experimental study on tie-rail placement combining both height and forward positions (Chapter 4) would allow us to analyze the direct effect of tie-rail placement on different outcome measures welfare such as clinical signs (e.g. injuries, lameness, BCS, feeding/rumination time), cleanliness (e.g. stall and cow cleanliness), production (e.g. milk yield and milk components), and cow ease of movement (lying-down and rising ability, lying behaviours, space usage within or outside of stall). The following section will introduce the different outcome measure that will be used in the experimental phase of the thesis.

2.4 Measures of dairy cow welfare, with a focus on how to measure cow ease of movement

Welfare is a comprehensive concept that can be measured in a number of ways. For instance, Fraser et al. (1997) identifies three main views of animal welfare. One view focuses on biological aspects such as health, growth and productivity, another view focuses on affective states of animals like pain and suffering, and the third view on animal welfare focuses on allowing animals to live in more natural conditions, enabling them to express their natural/normal behaviour. Thus, there are multiple measures that can be used to evaluate dairy cow welfare. Studies investigating the effect of stall design on cow welfare have used health measures such as clinical signs, environmental measures such as cow and stall cleanliness measures, level of performance such as production measures, and animal behaviour such as cow ease of movement measures to evaluate dairy cow welfare (Jensen, 1999; Haley et al., 2000; Fregonesi and Leaver, 2001; Tucker et al., 2005; Rushen et al., 2008).

2.4.1 *Clinical measures*

Some of the most common measures of assessing dairy cow welfare involve clinical signs. For example, level of injury has been used in studies as an outcome measure to compare different housing conditions, such as comparing different stall configuration (e.g. stall width and length, chain length, and tie-rail position) and stall surface (e.g. soft lying mats, rudder mats, and straw;Wechsler et al., 2000; Zurbrigg et al., 2005; Rushen et al., 2007; Nash et al., 2016; Bouffard et al., 2017). Different aspects of the stall have been found to be associated with different injury locations. For example, knee injuries such as hair loss have been associated with shorter chain length, smaller stalls, and tie-rail positioned closer to the rear curb of stall in tie-stalls, likely because cows do not have adequate space to rise and lie down causing cows to struggle on their knees creating friction between the knees and stall (Nash et al., 2016; Bouffard et al., 2017). Hock injuries such as swelling have been associated with short chains in tie-stalls, possibly due to restriction of movement (Zurbrigg et al., 2005; Bouffard et al., 2017). As mentioned above, neck injuries are often associated with tie-rail and feed rail position (Kielland et al., 2010; Bouffard et al., 2017). For instance, increasing forward position resulted in a reduced risk of neck injuries, likely because cows came in contact with the tie-rail less often while rising and eating (Bouffard et al., 2017). Examples of injury scoring systems can be found in Gibbons et al. (2012) and typically use a visual chart with different categories of severity and detailed definition of each category. For instance, scoring the lateral tarsal joints (hock) using a 0-3 scale: "No swelling with minor or no hair loss or broken hair (0); No swelling or minor swelling with thickness < 1 cm with bald area (1); Medium swelling thickness of 1-2.5 cm and/or lesion/scab, may have bald area (2); Major swelling thickness of > 2.5 cm (3)". Injuries are also important to assess as they are one of the main reasons for involuntary culling, which is when a farmer choose to cull a cow earlier than planned, for an uncontrolled reason. On farms in Quebec and the Maritimes, 6.3% of dairy cows are involuntarily culled due to injury and 15.3% of the reasons for reported mortality are due to injury/accident (Valacta, 2017). Neck, hock, and knee injuries are also one of the outcome measures of welfare assessed in Dairy Farmers of Canada's animal care assessment program proAction® initiative.

Another common clinical sign used to evaluate dairy cow welfare is lameness. Lameness may be used as an indicator of feet and leg problems and can be determined by how much weight cows puts on all four limbs (Whay et al., 1997; Leach et al., 2009; Palacio et al., 2017). Locomotion scoring systems are commonly used to assess lameness, such as the locomotion scoring system by Winckler and Willen (2001), which is based on gait evaluation on a scale of 1-5 where a score of 1-2 is considered not lame and a score of 3-5 is considered lame. Additionally, studies on tie-stall have developed a stall lameness scoring (SLS) method, where cows are scored in stall opposed to scoring cows when walking, as a reliable method of evaluating lameness with high a correlation found between observer scores from the locomotion scoring system and the stall lameness scoring system (Leach et al., 2009; Palacio et al., 2017). SLS is scored based on whether four behavioural indicators of lameness are present or not: (1) shifting weight from one hoof to the other; (2) cows placing one or both hind hooves on the edge of the stall while standing still; (3) repeatedly resting weight on one hoof more than the other; and (4) uneven weight bearing between left and right feet when cows move from side to side

(Palacio et al., 2017). If two or more of these behaviours are observed the cow is scored as lame (Leach et al., 2009; Palacio et al., 2017). Although this method may underestimate the prevalence of lameness compared to locomotion scoring, it provides an alternative scoring method for cows housed in tie-stall, where locomotion scoring is not feasible (Leach et al., 2009; Palacio et al., 2017). Studies have used lameness to evaluate housing conditions such as walking surfaces, stall configurations, and stall surfaces (Faull et al., 1996; Cook, 2003; Bernardi et al., 2009; Bouffard et al., 2017). Faull et al. (1996) found that smooth indoor walking surfaces resulted in a higher incidence of lameness. Lameness has also been found to be prevalent on farm; Bouffard et al. (2017) reported a lameness prevalence of 25.0% after evaluating 100 tie-stall farms in Canada. Feet and leg problems have been reported to be another major cause of involuntary culling. On farms in Quebec and Maritimes 14.9% of dairy cows are involuntarily culled and 7.3% of the reasons for reported mortality are due to feet and leg problems (Valacta, 2017). Dairy Farmers of Canada's animal care assessment program proAction® initiative will also be using lameness as one of outcome measures of welfare for on farm assessments.

Body condition score (BCS) is another clinical measure used to evaluate dairy cow welfare. BCS is usually based on scale scoring system used to determine whether a cow is too thin, too fat or at an ideal body condition. An example of BCS is using a 1-5 scale, 1 being very thin and 5 being very fat (DFC - NFACC, 2009). BCS have been found to be a useful and reliable tool to assess cows, with a high agreement among observers within a 0.5 score difference (weighted kappa = 0.79) and moderate agreement for exact scores (weighted kappa = 0.46, Vasseur et al., 2013). The Canadian Code of Practice states that if a cow has a BCS of ≤ 2 producers must take action to correct this (DFC - NFACC, 2009). On farms in Canada it was determined that 57% of farms had cows with BCS at 2 or lower (Vasseur et al., 2015). BCS will also be an outcome measure used to evaluate dairy cows on farm by the Dairy Farms of Canada animal care assessment program proAction® initiative.

Nutritional behaviours consisting of time spent ruminating and eating is an indicator of whether the nutritional needs of animals are met and could be used to evaluate dairy cow welfare. Rumination and feeding time can be recorded using recent technology such as CowManager SensOor and HR tags (Bikker et al., 2014; Dolecheck et al., 2015). In free-stall systems, CowManager SensOor's have been found to have a high correlation between visual observations and the technology (r = 0.93 for rumination and r = 0.88 for feeding time; Bikker et al., 2014). Few studies have looked at the effect of stall design on time spent feeding and ruminating. A study by Haley et al. (2000) found that feed intake was not different between the stall types tested: (1) loose-housed individually in box stalls and (2) standard tie-stalls. However, Haley et al. (2000) also found that cows stood idle without eating longer in tie-stalls compared to cows in loose-housed box stalls. Measuring the amount of time cows spend eating and ruminating would be an interesting outcome measure when comparing different stall configurations to determine whether novel stall configuration deters cows from eating and/or ruminating.

2.4.2 *Stall and cow cleanliness measures*

Another measure that can be used to assess dairy cow welfare is stall and cow cleanliness measures. Scoring systems are usually used to evaluate stall and cow cleanliness measures. An example of stall and cow cleanliness scoring is described in Vasseur et al. (2015) and can be found on the Canadian Dairy Research Portal (https://www.dairyresearch.ca/cow-comfort.php#self). Cow cleanliness is scored on a scale of 0-3: 0 represents that the area of the cow is clean or has <50% of fresh manure and 3 represents the entire area being contaminated with dried, caked manure. Stall cleanliness is scored on a scale of 1-5: 1 represents a clean stall with no presence of manure or faeces and 5 represents the entire stall being dirty. Cow cleanliness has been associated with diseases such as mastitis. For instance, a study by Schreiner and Ruegg (2003) found that an increase in dirty udders was associated with an increase of linear somatic cells scores and an increase in the prevalence of intramammary contagious and environmental pathogens. Compared to cows with clean udder and leg scores, milk samples from cows with dirty udder and leg scores were more likely to contain major pathogens (Schreiner and Ruegg, 2003). A study by Breen et al. (2009) had similar findings, where very dirty udders were found to be associated with increased risk of clinical mastitis. This is important because together high somatic cell counts and mastitis results in 23.7% of involuntary culling on farms in Quebec and Maritimes (Valacta, 2017). Bergsten and Pettersson (1992) observed less faeces deposited in the stall resulted in cleaner cows; thus, cleaner stalls likely result in cleaner cows. Studies have used cow and stall cleanliness to evaluate stall base and stall configuration. For instance, when comparing concrete stall bases to conventional rubber mats and comfort mats. Herlin (1997) found that more faeces covered the concrete surface compared to the other treatments. Cleanliness is another outcome measure that is used by Dairy Farmers of Canada’s assessment program proAction® initiative to evaluate dairy cow welfare and milk quality.

2.4.3 ***Production measures***

Milk production measures have been used as indicators of dairy cow welfare. For instance, reduced milk yield can be associated with health issues such as, mastitis, diarrhoea, ketosis and milk fever (Bareille et al., 2003). Milk yield has also been found to decrease when dairy cows are under acute stress, such as in an unfamiliar environment (Rushen et al., 2001). Previous studies have used production measures like milk yield to assess different housing designs. For example, Tucker et al. (2004) used milk production to assess the effect of stall width on dairy cow welfare and found that milk production was not affected by stall width. Additionally, producers put a lot of importance in milk production factors. For instance, milk production factors account for 56.7% of the rational behind why cows are voluntarily culled (removed cows from the herd) from dairy farms in Quebec and Maritimes (Valacta, 2017). Low milk production accounts for 22.3% of the reason producers voluntary cull dairy cows (remove cows from the herd) in Quebec and Maritimes (Valacta, 2017). Low fat and protein production in the milk accounts for 0.3 and 0.05% of the reason for voluntary culling of dairy cows on Quebec and Maritimes farms (Valacta, 2017). Production measures are not only a potential outcome measure of welfare but also hold a lot of importance to dairy farmers, making production an important outcome measure when proposing new recommendations to improve the acceptance of recommendations by dairy producers.

2.4.4 ***Cow ease of movement measures***

As mentioned in Section 2.1, the general public has been found to have concerns about providing cows with housing conditions that allow them to exhibit natural behaviours (Prickett et al., 2010; Schuppli et al., 2014). Thus, cow ease of movement measures are of particular interest in stall design, as it is likely that proper stall design may allow cows to move more naturally. Cow ease of movement can be defined as when cows move similarly, and with the same amount of ease, as they would with a soft flooring base and no restrictions around them (e.g. at pasture). Normal lying and rising motions are ease of movement outcome measures that have been described in the literature. Normal motions for lying-down behaviour are described as the cow first performing intention movements by sniffing the ground while sweeping their head back and forth before descending to their knees, then lowering the rest of their body to the ground (Figure 2.4A, Lidfors, 1989; Wechsler et al., 2000). Studies have described rising motions in cows as standing up naturally by first resting on their knees, raising their hind quarters and then extending the forelegs (Figure 2.4B, Lidfors, 1989; Wechsler et al., 2000). The duration of a normal lying motion should be less then 5.2 s starting from when cow first bends their front leg, and a normal duration for rising motion is between 3-5 s from when the cow bobs its head forward (Lensink and Leruste, 2006; Welfare Quality, 2009). Abnormal behaviours for lying and rising motions have also been described in the literature. Abnormal lying consists of cows lying down first onto their hind quarters and then going down onto their knees, a long duration of intention movements and lying motion, contact with housing equipment such as divider bar or tie-rail, numerous attempts of lying, and slipping (Lidfors, 1989; Herlin, 1997; Wechsler et al., 2000; Corazzin et al., 2010; Plesch et al., 2010; Popescu et al., 2013). Abnormal rising consists of a long duration of the rising motion, multiple attempts of rising, collision or contact with housing equipment such as the divider bar or tie-rail, slipping, horse-like rising (rising onto forelegs first), resting on carpal joints for > 10 s and crawling backwards on knees (Lidfors, 1989; Wechsler et al., 2000; Regula et al., 2004; Corazzin et al., 2010; Plesch et al., 2010). Lying and rising ability has been found to be a fairly reliable measure of welfare. Studies have used the rising and lying ability of the cows to measure the comfort of different housing systems, such as loose or tied cows and aspects of the stall such as bedding and stall design (Table 2.7; Table 2.8). For example, studies have found that stall base and stall types in cubicle housing did not have an effect on rising ability (Herlin, 1997; Wechsler et al., 2000; Abade et al., 2015). However, some studies found that lying ability improved with more compressible/soft stall bases (Krohn and Munksgaard, 1993; Herlin, 1997). This is likely because the cushioning is more comfortable during lying motion. Lying ability improved when cows were housed in loose housing compared to tie-stall housing (Krohn and Munksgaard, 1993), with heifers moved from pens to tie-stalls showing increased difficulty in lying, especially post-move (Jensen, 1999). This could be an indication that lying ability is impaired when cows are housed in more restrictive environments. Overall, lying and rising ability is an exciting outcome measure of welfare that has the potential to visually illustrate the discomfort of cows in different environments.

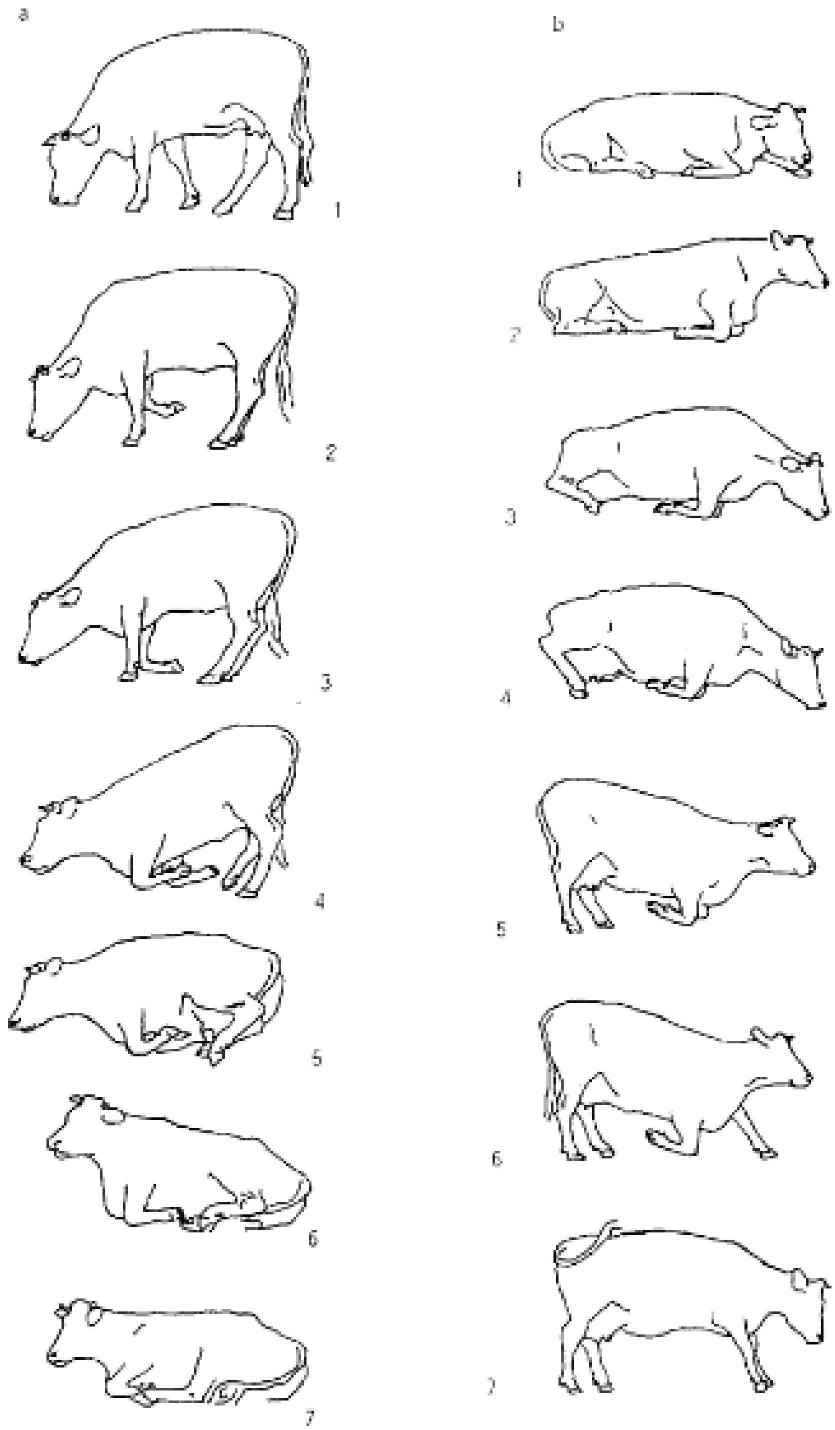

Figure 2.4 (A) lying down motion and (B) rising motion (Schnitzer, 1971)

Table 2.7 Studies using rising ability to determine the comfort of different stall designs

Cow ease of movement measure	**Housing type**	Method of Measurement	Treatments	Comparison[1]	Significance	n	Reference
Total duration of rising event	**Cubicle systems**	Video observation	Stall base: (1) Straw bedding (compact mattress of straw and cow dung) (2) CowComfort mat (foamed polyurethane) (3) Kraiburg mat (conventional rubber mat, underlaid with foam rubber) (4) Mouflex mat (Tubes of polypropylene and nylon filled with granulated rubber and covered with layer of polypropylene) (5) Pasture mat (Tubes of polypropylene and nylon filled with granulated rubber and covered with a layer of polpropylene)	s/event: (1) 7.7 (2) 6.6 (3) 6.8 (4) 7.9 (5) 8.3	NS[2]	20 cows	Wechsler et al. (2000)
	Free-stall	Video observation	Stall type: (1) Conventional stall (with neck-rail and metal stall dividers) (2) Alternative stall (no neck-rail or stall dividers other than a wooden board protruding a little above the lying surface)	s/event: (1) 5.8 ± 0.31 (2) 5.1 ± 0.31	$P = 0.09$	48 cows	Abade et al. (2015)
	Loose house cubicles	Video observation	Stall base: (1) Concrete (2) Rubber mats (3) Comfort mats	s/event: (1) 9 ± 0.2 (2) 8 ± 0.2 (3) 8 ± 0.2	NS	15 cows	Herlin (1997)
Rate of difficulties when rising: crawling before rising (shuffling back on knees), breaks in rising movement, and slipping	**Cubicle systems**	Video observation	Stall base: (1) Straw bedding (compact mattress of straw and cow dung) (2) Cow Comfort mat (foamed polyurethane) (3) Kraiburg mat (conventional rubber mat, underlaid with foam rubber) (4) Mouflex mat (Tubes of polypropylene and nylon filled with granulated rubber) (5) Pasture mat (Tubes of polypropylene and nylon filled with granulated rubber and covered with a layer of polpropylene)	Incidence per movement: (1) 0.25 (2) 0.02 (3) 0.16 (4) 0.23 (5) 0.25	NS	20 cows	Wechsler et al. (2000)
Attempts	**Loose house cubicles**	Video observation	Stall base: (1) Concrete (2) Rubber mats (3) Comfort mats	n/d: (1) 2 (2) 2 (3) 0	NS	15 cows	Herlin (1997)
Abnormal/horse rising (getting up on forequarters first)	**Loose house cubicles**	Video observation	Stall base: (1) Concrete (2) Rubber mats (3) Comfort mats	n/d: (1) 1 n/d (2) 0 n/d (3) 0 n/d	NS	15 cows	Herlin (1997)

[1]Compares the housing environments effect on rising ability

[2]NS = not significant

Table 2.8 Studies using lying ability to determine the comfort of different stall designs and housing types

Cow ease of movement measure	Stall type/ Housing type	Method of Measurement	Treatments	Comparison[1]	Significance	n	Reference
Duration of lying event	**Cubicle systems**	Video observation	Stall base: (1) Straw bedding (compact mattress of straw and cow dung) (2) CowComfort mat (foamed polyurethane) (3) Kraiburg mat (conventional rubber mat, underlaid with foam rubber) (4) Mouflex mat (Tubes of polypropylene and nylon filled with granulated rubber and covered with layer of polypropylene) (5) Pasture mat (Tubes of polypropylene and nylon filled with granulated rubber and covered with a layer of polpropylene)	s/event: (1) 4.6 (2) 5.1 (3) 4.8 (4) 4.9 (5) 4.7	NS[2]	20 cows	Wechsler et al. (2000)
	Tie-stall & straw-bedded pens	Video observation	Housing type/Period of time cows are tethered: (1) 3 days tethered (2) 10 days tethered (3) 24 days tethered (4) pen	s/event: longer for heifers tethered for 3 days compared to 10 and 24 days or heifers housed in pen	$P < 0.001$	48 cows	Jensen (1999)
	Pasture & deep bedded & tie-stall	Video observation	Housing/stall type: (1) Loose housing: Pasture, milked x2 daily (2) Loose housing: Deep Bedding, milked x2 daily (3) Tie-stall: Concrete floor + 1kg straw, milked x2 daily, no exercise (4) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, no exercise (5) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, exercise	s/event: (1) 7 ± 1.6^{a} (2) 8 ± 1.7^{a} (3) 14 ± 1.9^{b} (4) 9 ± 1.7^{a} (5) 8 ± 1.7^{a}	$^{abcd}P < 0.05$[3]	24 pairs of twin cows	Krohn and Munksgaard (1993)
	Free-stall	Video observation	Stall type: (1) Conventional stall (with neck-rail and metal stall dividers) (2) alternative stall (no neck-rail or stall dividers other than a wooden board protruding a little above the lying surface)	s/event: (1) 6.3 ± 0.21 (2) 5.9 ± 0.21	$P = 0.15$	48 heifers	Abade et al. (2015)
	Loose house cubicles	Video observation	Stall base: (1) Concrete (2) Rubber mats (3) Comfort mats	s/event: (1) 6 ± 0.3^{ab} s (2) 6 ± 0.3^{b} s (3) 5 ± 0.3^{a} s	a-b and b-c $P < 0.05$, a-c $P < 0.01$, and a-d $P < 0.001$	15 cows	Herlin (1997)
Duration of intention movements	**Pasture & deep bedded loose housing & tie-stall**	Video observation	Housing/stall type: (1) Loose housing: Pasture, milked x2 daily (2) Loose housing: Deep Bedding, milked x2 daily (3) Tie-stall Concrete floor + 1kg straw, milked x2 daily, no exercise (4) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, no exercise	s/event: (1) 8 ± 4.0^{a} (2) 21 ± 4.6^{b} (3) 51 ± 5.1^{c} (4) 49 ± 4.7^{c} (5) 42 ± 4.7^{c}	$^{abcd}P < 0.05$	24 pairs of twin cows	Krohn and Munksgaard (1993)

			(5) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, exercise				
	Loose house cubicles	Video observation	Stall base: (1) Concrete (2) Rubber mats (3) Comfort mats	s/event: (1) 108 ± 8.5[a] (2) 79 ± 8.5[b] (3) 50 ± 8.5[c]	a-b and b-c $P < 0.05$, a-c $P < 0.01$, and a-d $P < 0.001$	15 cows	Herlin (1997)
Head sweeping movements (lying intention movements)	**Tie-stall**	Video observation	Stall base: (1) Concrete (2) Mattress	% of total observations: (1) 3.01 ± 0.66 (2) 3.10 ± 0.61	$P > 0.10$	16 cows	Haley et al. (2001)
Interrupted intention movements (cow lifts head after swing head from side to side)	**Tie-stall**	Video observation	Front of stall opening: (1) Narrow (2) Wide	% of total observations: (1) 2.55 ± 0.43 (2) 1.66 ± 0.33	NS	16 Holstein	Haley et al. (2001)
	Pasture & Deep bedded loose housing & Tie-stall	Video observation	Housing/stall type: (1) Loose housing: Pasture, milked x2 daily (2) Loose housing: Deep Bedding, milked x2 daily (3) Tie-stall: Concrete floor + 1kg straw, milked x2 daily, no exercise (4) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, no exercise (5) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, exercise	% of lying-down events in which 1 interruption occurred: (1) 11.4[a] (2) 15.9[a] (3) 24.8[b] (4) 25.6[b] (5) 30.3[b]	$^{abcd}P < 0.05$	24 pairs of twin cows	Krohn and Munksgaard (1993)
	Pasture & Deep bedded loose housing & Tie-stall	Video observation	Housing/stall type: (1) Loose housing: Pasture, milked x2 daily (2) Loose housing: Deep Bedding, milked x2 daily (3) Tie-stall: Concrete floor + 1kg straw, milked x2 daily, no exercise (4) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, no exercise (5) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, exercise	% of lying-down events in which 2 interruptions occurred: (1) 1.0[a] (2) 10.3[b] (3) 20.5[c] (4) 22.0[c] (5) 17.7[c]	$^{abcd}P < 0.05$	24 pairs of twin cows	Krohn and Munksgaard (1993)
	Pasture & Deep bedded loose housing & Tie-stall	Video observation	Housing/stall type: (1) Loose housing: Pasture, milked x2 daily (2) Loose housing: Deep Bedding, milked x2 daily (3) Tie-stall: Concrete floor + 1kg straw, milked x2 daily, no exercise (4) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, no exercise (5) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, exercise	% of lying-down bouts in which ≥ 3 interruptions occurred: (1) 1.0[a] (2) 15.9[b] (3) 33.3[d] (4) 22.8[c] (5) 22.5[c]	$^{abcd}P < 0.05$	24 pairs of twin cows	Krohn and Munksgaard (1993)
	Tie-stall & straw-bedded pens	Video observation	Housing type/ Period of time cows are tethered: (1) 3 days tethered (2) 10 days tethered (3) 24 days tethered (4) Pens	n/event: higher interruptions for heifers tethered for 3 days compared to heifers tethered for 10 and 23 days or housed in pens	$P < 0.001$	48 heifers	Jensen (1999)
Standing up after starting to lie down	**Pasture & Deep bedded**	Video observation	Housing/stall type: (1) Loose housing: Pasture, milked x2 daily (2) Loose housing: Deep Bedding, milked x2 daily	% of lying-down events in which 1 interruption occurred:	$^{abcd}P < 0.05$	24 pairs of twin cows	Krohn and Munksgaard (1993)

	loose housing & Tie-stall		(3) Tie-stall: Concrete floor + 1kg straw, milked x2 daily, no exercise (4) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, no exercise (5) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, exercise	(1) 6.9^{a} (2) 10.8^{a} (3) 22.6^{b} (4) 24.9^{b} (5) 25.6^{b}			
	Pasture & Deep bedded loose housing & Tie-stall	Video observation	Housing/stall type: (1) Loose housing: Pasture, milked x2 daily (2) Loose housing: Deep Bedding, milked x2 daily (3) Tie-stall: Concrete floor + 1kg straw, milked x2 daily, no exercise (4) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, no exercise (5) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, exercise	% of lying-down bouts in which 2 interruptions occurred: (1) 0.5^{a} (2) 3.3^{a} (3) 11.8^{b} (4) 9.2^{b} (5) 7.3^{b}	$^{abcd}P < 0.05$	24 pairs of twin cows	Krohn and Munksgaard (1993)
	Pasture & Deep bedded loose housing & Tie-stall	Video observation	Housing/stall type: (1) Loose housing: Pasture, milked x2 daily (2) Loose housing: Deep Bedding, milked x2 daily (3) Tie-stall: Concrete floor + 1kg straw, milked x2 daily, no exercise (4) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, no exercise (5) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, exercise	% of lying-down bouts in which ≥ 3 interruptions occurred: (1) $-^{a}$ (2) 0.5^{a} (3) 10.5^{c} (4) 5.6^{b} (5) 4.2^{b}	$^{abcd}P < 0.05$	24 pairs of twin cows	Krohn and Munksgaard (1993)
	Tie-stall & straw-bedded pens	Video observation	Housing type/Period of time cows are tethered: (1) 3 days tethered (2) 10 days tethered (3) 24 days tethered (4) pen	n/event: more for heifers tethered for 3 and 10 days compared to cows in pen	$P < 0.001$	48 heifers	Jensen (1999)
Rate of difficulties when rising: duration of intention movements, slipping when lying down and standing up again after starting to lie down	**Cubicle systems**	Video observation	Stall base: (1) Straw bedding (compact mattress of straw and cow dung) (2) CowComfort mat (foamed polyurethane) (3) Kraiburg mat (conventional rubber mat, underlaid with foam rubber) (4) Mouflex mat (Tubes of polypropylene and nylon filled with granulated rubber) (5) Pasture mat (Tubes of polypropylene and nylon filled with granulated rubber and covered with a layer of polpropylene)	Incidence per movement: (1) 0.11 (2) 0.22 (3) 0.35 (4) 0.29 (5) 0.23	NS	20 cows	Wechsler et al. (2000)

[1]Compares the housing environments effect on lying ability

[2] NS = not significant with a *P*-value greater than 0.05

[3]Different letters represents a significant difference between the treatment

Another aspect of ease of movement in the housing environment are lying behaviours, which consists of: lying time, number of lying bouts, and lying bout duration. Cows will spend approximately 10-14 h/d lying in tie-stall and/or free-stall housing environments (Tucker et al., 2004; Fregonesi et al., 2007; Chapinal et al., 2009; Tucker et al., 2009). Moreover, dairy cows have been shown to highly prioritize lying down and resting activities (Metz, 1985; Jensen et al., 2005).Thus, lying time has been used in studies to evaluate the welfare of dairy cows (Table 2.8). Studies have found that lying time may differ depending on bedding depth and material (Tucker et al., 2003; Tucker et al., 2009), stall base (Haley et al., 2001; Rushen et al., 2007), housing types (Haley et al., 2000), and stall configuration (Tucker et al., 2004). Providing cows with more space, such as a providing a wider stall or pen housing, may result in cows spending more time lying (Haley et al., 2000; Tucker et al., 2004). However, Krohn and Munksgaard (1993) found that cows spent less time lying when housed in loose housing with pasture access compared to cows housed in tie-stall. This decrease in lying time for cows at pasture is likely due to the fact that the cows spent more time walking in search of quality grasses and possibly engaging in other activities, like social behaviours (Krohn and Munksgaard, 1993). Studies have also found that lying time increases when the stall base is comprised of a softer and/or more compressible material or contained more bedding (Haley et al., 2001; Tucker et al., 2003; Tucker and Weary, 2004; Rushen et al., 2007; Tucker et al., 2009). These results suggest that cows may feel more comfortable lying in more spacious environments and on stall bases which are softer and/or more compressible.

Additionally, studies have used number of lying bouts and lying bout duration to evaluate dairy cow welfare (Table 2.9). Number of lying bouts is defined as the number of times cows transition between lying and standing, and the duration of a lying bout is defined as the length of time cows spend lying before rising again. An increased number of lying bouts can signify that a cow feels more at ease transitioning from standing to lying and vice versa. Studies have found that bedding depth and material (Krohn and Munksgaard, 1993; Tucker et al., 2003; Tucker et al., 2009), stall base (Krohn and Munksgaard, 1993; Haley et al., 2001; Rushen et al., 2007), housing type (Krohn and Munksgaard, 1993; Haley et al., 2000), and stall configuration (Tucker et al., 2004) have an effect on the number of lying bouts and/or lying bout duration. For example, Haley et al. (2000) found that cows housed in pens compared to tie-stall housing had an increased number of lying bouts, but no change in lying bout duration. This is possibly because cows felt more at ease rising and lying in more opens areas. Conversely, Krohn and Munksgaard

(1993) found that loose-housed cows with pasture access had a reduced number of lying bouts compared to cows housed in tie-stall. However, Krohn and Munksgaard (1993) hypothesized that cows housed in tie-stall may experience more disturbances in the barn due to increased milking frequency and/or movement to allow access to exercise. When increasing the stall width in a free-stall system, Tucker et al. (2004) found that lying bout duration was not affected; however, the duration of lying bouts increased for cows housed wider stalls, possibly due to cows coming in contact with the stall dividers less often. Studies also found that having a more compressible stall base material and increasing bedding depth increases the number of lying bouts and may reduce lying bout duration (Haley et al., 2001; Tucker and Weary, 2004; Rushen et al., 2007; Tucker et al., 2009). It is likely that the number of lying bouts increase and lying bout duration decreases when the stall base is softer and more compressible, as cows feel more at ease transitioning between lying and standing and likely experience a reduced impact and friction between their legs and the stall base during rising and lying motions. To measure lying behaviours, studies have started to use technology such as leg mounted accelerometers. Validation studies found that accelerometers such as Hobo Pendant G data loggers (Bonk et al., 2013; Mattachini et al., 2013), IceQubes (Kok et al., 2015), Ice Tags (Mattachini et al., 2013), and Afimilk pedometers (Felton et al., 2012) are an easy and reliable way to measure lying time, frequency of lying bouts, and duration of lying bouts.

Table 2.9 Studies using lying behaviours to measure dairy cow welfare

Cow ease of movement measure	**Stall type/ Housing type**	Method of Measurement	Treatments	Comparison[1]	Significance	n	Reference
Lying time	**Free-stall**	Video observation	Bedding: (1) Deep bedded sawdust (2) Deep bedded sand (3) Geotextile mattress covered with 2-3 cm of sawdust	h/d: (1) 15.0 ± 0.40[b] (2) 14.9 ± 0.62[b] (3) 13.3 ± 0.54[a]	[abcd]$P \leq 0.05$[2]	12 cows	Tucker et al. (2003)
	Free-stall	Video observation	Bedding: (1) Deep bedded sawdust (2) Deep bedded sand (3) Geotextile mattress covered with 2-3 cm of sawdust	h/d: (1) 14.3 ± 0.83[b] (2) 10.9 ± 1.57[a] (3) 14.3 ± 0.54[b]	[abcd]$P \leq 0.05$	12 cows	Tucker et al. (2003)
	Pens & tie-stall	Video observation	Housing type: (1) Large pens (2) Tie-stall	h/d: (1) 14.73 ± 0.91 (2) 10.51 ± 1.03	$P = 0.006$	8 cows	Haley et al. (2000)
	Free-stall	Video observation	Stall type: (1) Conventional stall (with neck-rail and metal stall dividers) (2) Alternative stall (no neck-rail or stall dividers other than a wooden board protruding a little above the lying surface)	Overall ave. h/d across trt.[3]: (1) 13 (2) 13	$P = 0.23$	48 cows	Abade et al. (2015)
	Pasture & deep bedded & tie-stall	Video observation	Housing/stall type: (1) Loose housing: Pasture & Deep Bedding (2) Tie-stall: Concrete floor + 1kg straw, no exercise (3) Tie-stall: Rubber mats + 2kg straw, no exercise (4) Tie-stall: Rubber mats + 2kg straw, exercise	min/24h: (1) 605 ± 28[a] (2) 706 ± 19[b] (3) 781 ± 18[b] (4) 760 ± 18[b]	[abcd]$P > 0.05$	24 pairs twin cows	Krohn and Munksgaard (1993)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	h/d: (1) 10.42 ± 0.42 (2) 12.25 ± 0.33	$P = 0.001$	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Stall fronts: (1) Narrow (2) Wide	h/d: (1) 12.57 ± 0.42 (2) 13.28 ± 0.44	NS[4]	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Rubber mats	h/d: (1) 8.13 ± 0.29 (2) 9.37 ± 0.29	$P = 0.051$	24 cows	Rushen et al. (2007)
	Free-stall	Video observation	Bedding: (1) Pasture mat with 0 kg sawdust (2) Pasture mat with 1 kg sawdust (3) Pasture mat with 7.5 kg sawdust	h/d: (1) 12.3 ± 0.53 (2) 12.5 ± 0.53 (3) 13.8 ± 0.53	$P = 0.01$[5]	10 cows	Tucker and Weary (2004)
	Free-stall	Video observation	Stall width: (1) Narrow (112 cm) (2) Wide (132 cm)	h/d: (1) 9.6 ± 0.29 (2) 10.8 ± 0.29	$P = 0.01$	15 cows	Tucker et al. (2004)

	Free-stall	Video observation	Stall length: (1) Short (229 cm) (2) Long (274 cm)	h/d: (1) 9.9 ± 0.29 (2) 10.5 ± 0.29	$P = 0.16$	15 cows	Tucker et al. (2004)
	Tie-stall	Gemini data loggers	Amount of shavings: (1) 3 kg/stall (2) 9 kg/stall (3) 15 kg/stall (4) 24 kg/stall	h/d: (1) 11.0 ± 0.24 (2) 11.7 ± 0.24 (3) 11.6 ± 0.24 (4) 12.1 ± 0.24	$P_{\text{weight}} = 0.004$ $P_{\text{compressibility}} = 0.004$	12 cows	Tucker et al. (2009)
	Tie-stall	Gemini data loggers	Amount of straw: (1) 1 kg/stall (2) 3 kg/stall (3) 5 kg/stall (4) 7 kg/stall	h/d: (1) 11.2 ± 0.20 (2) 12.0 ± 0.20 (3) 11.8 ± 0.20 (4) 12.4 ± 0.20	$P_{\text{weight}} = 0.001$ $P_{\text{compressibility}} = <0.001$	12 cows	Tucker et al. (2009)
	Tie-stall	Gemini data loggers	Amount of straw: (1) 0.5 kg/stall (2) 1 kg/stall (3) 2 kg/stall (4) 3 kg/stall	h/d: (1) 11.9 ± 0.32 (2) 11.3 ± 0.32 (3) 12.0 ± 0.32 (4) 11.7 ± 0.32	$P_{\text{weight}} = 0.833$ $P_{\text{compressibility}} = 0.703$	12 cows	Tucker et al. (2009)
Number (n) of lying bouts	**Free-stall**	Video observation	Bedding: (1) Deep bedded sawdust (2) Deep bedded sand (3) Geotextile mattress covered with 2-3 cm of sawdust	n/d: 10.5 ± 0.57[b] 10.0 ± 0.48[b] 8.5 ± 0.55[a]	[abcd]$P \leq 0.05$	12 cows	Tucker et al. (2003)
	Pens & Tie-stall	Video observation	Housing type: (1) Large pens (2) Tie-stall	n/d: (1) 13.63 ± 1.45 (2) 8.21 ± 1.16	$P = 0.024$	8 cows	Haley et al. (2000)
	Pasture & Deep bedded & Tie-stall	Video observation	Housing/stall type: (1) Loose housing: Pasture & Deep Bedding, milked x2 daily (2) Tie-stall: Concrete floor + 1kg straw, milked x2 daily, no exercise (3) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, no exercise (4) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, exercise	n/15 h: (1) 8.0 ± 0.5[a] (2) 9.9 ± 0.5[b] (3) 10.5 ± 0.5[bc] (4) 11.5 ± 0.5[c]	[abcd]$P < 0.05$	24 pairs of twin cows	Krohn and Munksgaard (1993)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	n/d: (1) 9.05 ± 0.94 (2) 13.13 ± 1.12	$P = 0.001$	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Front of stall opening: (1) Narrow (2) Wide	ave. n/d across trt.: (1) 12.5 (2) 12.5	NS	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Rubber mats	n/d: (1) 6.23 ± 0.42 (2) 9.62 ± 0.42	$P = 0.01$	24 cows	Rushen et al. (2007)
	Free-stall	Video observation	Bedding: (1) Pasture mat with 0 kg sawdust (2) Pasture mat with 1 kg sawdust (3) Pasture mat with 7.5 kg sawdust	n/d: (1) 8.5 ± 0.62 (2) 9.3 ± 0.62 (3) 10.0 ± 0.62	$P = 0.04$	10 cows	Tucker and Weary (2004)

	Free-stall	Video observation	Stall width: (1) Narrow (112 cm) (2) Wide (132 cm)	n/d: (1) 8.4 ± 0.37 (2) 8.1 ± 0.37	$P = 0.58$	15 cows	Tucker et al. (2004)
	Free-stall	Video observation	Stall length: (1) Short (229 cm) (2) Long (274 cm)	n/d: (1) 8.0 ± 0.37 (2) 8.6 ± 0.37	$P = 0.19$	15 cows	Tucker et al. (2004)
	Tie-stall	Gemini data loggers	Amount of shavings: (1) 3 kg/stall (2) 9 kg/stall (3) 15 kg/stall (4) 24 kg/stall	n/d: (1) 12.5 ± 0.61 (2) 13.2 ± 0.61 (3) 13.3 ± 0.61 (4) 13.8 ± 0.61	$P_{weight} = 0.163$ $P_{compressibility} = 0.169$	12 cows	Tucker et al. (2009)
	Tie-stall	Gemini data loggers	Amount of straw: (1) 1 kg/stall (2) 3 kg/stall (3) 5 kg/stall (4) 7 kg/stall	n/d: (1) 11.3 ± 0.40 (2) 12.6 ± 0.40 (3) 12.8 ± 0.40 (4) 13.3 ± 0.40	$P_{weight} = 0.003$ $P_{compressibility} = 0.003$	12 cows	Tucker et al. (2009)
	Tie-stall	Gemini data loggers	Amount of straw: (1) 0.5 kg/stall (2) 1 kg/stall (3) 2 kg/stall (4) 3 kg/stall	n/d: (1) 12.3 ± 0.41 (2) 12.2 ± 0.41 (3) 12.7 ± 0.41 (4) 12.7 ± 0.41	$P_{weight} = 0.361$ $P_{compressibility} = 0.417$	12 cows	Tucker et al. (2009)
Lying bout duration	**Pens & tie-stall**	Video observation	Housing type: (1) Large pens (2) Tie-stall	Min/bout: (1) 68.00 ± 5.68 (2) 86.72 ± 13.20	$P = 0.1530$	8 cows	Haley et al. (2000)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	Min/d: (1) 77.71 ± 6.70 (2) 61.92 ± 5.08	$P = 0.01$	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Front of stall opening: (1) Narrow (2) Wide	ave. for min/d across trt.: 66 min/d	NS	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Rubber mats	Min/d: (1) 78.29 min/d (2) 58.44 min/d	$P = 0.07$	24 cows	Rushen et al. (2007)
	Free-stall	Video observation	Bedding: (1) Pasture mat with 0 kg sawdust (2) Pasture mat with 1 kg sawdust (3) Pasture mat with 7.5 kg sawdust	h/bout: (1) 1.5 ± 0.10 (2) 1.4 ± 0.10 (3) 1.4 ± 0.10	$P = 0.37$	10 cows	Tucker and Weary (2004)
	Free-stall	Video observation	Stall width: (1) Narrow (112 cm) (2) Wide (132 cm)	h/bout: (1) 1.3 ± 0.05 (2) 1.5 ± 0.05	$P = 0.01$	15 cows	Tucker et al. (2004)
	Free-stall	Video observation	Stall length: (1) Short (229 cm) (2) Long (274 cm)	h/bout: (1) 1.4 ± 0.05 (2) 1.4 ± 0.05	$P = 0.79$	15 cows	Tucker et al. (2004)
	Tie-stall	Gemini data loggers	Amount of shavings: (1) 3 kg/stall (2) 9 kg/stall (3) 15 kg/stall (4) 24 kg/stall	Min/bout: (1) 55 ± 1.9 (2) 56 ± 1.9 (3) 55 ± 1.9 (4) 56 ± 1.9	$P_{weight} = 0.637$ $P_{compressibility} = 0.637$	12 cows	Tucker et al. (2009)

Tie-stall	Gemini data loggers	Amount of straw: (1) 1 kg/stall (2) 3 kg/stall (3) 5 kg/stall (4) 7 kg/stall	Min/bout: (1) 63 ± 1.5 (2) 61 ± 1.5 (3) 60 ± 1.5 (4) 60 ± 1.5	P_{weight} = 0.152 $P_{compressibility}$ = 0.201	12 cows	Tucker et al. (2009)
Tie-stall	Gemini data loggers	Amount of straw: (1) 0.5 kg/stall (2) 1 kg/stall (3) 2 kg/stall (4) 3 kg/stall	Min/bout: (1) 59 ± 2.3 (2) 57 ± 2.3 (3) 59 ± 2.3 (4) 58 ± 2.3	P_{weight} = 0.791 $P_{compressibility}$ = 0.899	12 cows	Tucker et al. (2009)

[1]Compares the housing environments effect on lying behaviours

[2]Different letters represents a significant difference between the treatments

[3]Ave. = average and trt. = treatment

[4] NS = not significant with a *P*-value greater than 0.05

[5]*P*-values are a linear contrast

Othere indicators of cow ease of movement that can be used to evaluate dairy cow welfare are the postures exhibited by the cow when lying (Table 2.10). Different lying postures consist of different head positions (head resting back against their body, head on floor and head upright), leg positions (front and/or hind leg tuck or extended, both legs extended and both legs tucked, hind leg in mid-position), and body positions (lying flat on her side or more upright on her sternum). These positions could be indicators of better rest. When cows rest their head against their body or an object, it is considered a time when she is in deep sleep (rapid eye movement; Ruckebusch, 1975; Ternman et al., 2014). Additionally, cows lying with extended legs could be an indicator that cows feel as if they have the space to stretch out, as demonstrated by Boyer et al. (2018) where cows housed in wider tie-stalls increased their utilization of the extra space provided. Studies have shown that housing type and stall base may have an effect on the lying postures performed (Krohn and Munksgaard, 1993; Haley et al., 2000; Haley et al., 2001). For example, Krohn and Munksgaard (1993) found that cows with fewer space restrictions, such as with loose housing and pasture, positioned their head against their body and on the ground more often than cows housed in tie-stalls. However, when Haley et al. (2000) compared the lying positions between pens and tie-stalls, they found that there was no difference in the head resting position (body or ground) and lying positions (head positioned up, front leg tucked, and hind leg positioned in the middle) were more frequently observed in cows housed in pens. This could be due to the fact that the three lying postures listed above were commonly observed and cows spent more time lying in the pens than in the tie-stalls. Providing more space does not always seem to result in changes in lying postures, but cows may still utilize the space they are given. For example, in tie-stalls with a wider gap at the front of stall, cows spent more time with their head in the manger area compared to cows with a narrower gap at the front of the stall (Haley et al., 2001). Cows housed on softer stall surfaces compared to harder stall surfaces have also been linked to an increase in time spent in commonly observed lying positions such as cows with their head up, front leg tucked, and hind leg positioned in middle (Haley et al., 2001; Rushen et al., 2007). This is because cows on softer stall surfaces spend more time lying, and that extra lying time mainly occurred when their head was up; therefore, the behaviours were observed more often than in cows on harder stall bases (Haley et al., 2001; Rushen et al., 2007). Space allowance may affect how cows position themselves when lying and increases length of lying, but space allowance along with stall base softness may not have an effect on the duration of deep sleep.

Table 2.10 Studies using lying positions to measure dairy cow welfare

Cow ease of movement measure	**Stall type/ Housing type**	Method of Measurement	Treatments	Comparison[1]	Significance	n	Reference
Head position: back against the body	**Pens & tie-stall**	Video observation	Housing type: (1) Large pens (2) Tie-stall	%/d: (1) 5.31 ± 0.69 (2) 4.83 ± 0.90	*P* = 0.6494	8 cows	Haley et al. (2000)
	Pasture & deep bedded loose housing & tie-stall	Video observation	Housing/stall type: (1) Loose housing: Pasture, milked x2 daily (2) Loose housing: Deep Bedding, milked x2 daily (3) Tie-stall: Concrete floor + 1kg straw, milked x2 daily, no exercise (4) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, no exercise (5) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, exercise	%/total lying time: (1) 11.5 ± 1.5[a] (2) 8.4 ± 0.5[ab] (3) 5.4 ± 0.5[c] (4) 4.8 ± 0.5[c] (5) 5.8 ± 0.5[c]	[abcd]*P* < 0.05[2]	24 pairs of twin cows	Krohn and Munksgaard (1993)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	% of total observations: (1) 4.28 ± 0.58 (2) 4.80 ± 0.43	*P* > 0.10	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Front of stall opening: (1) Narrow (2) Wide	% of total observations: (1) 4.82 ± 0.44 (2) 5.42 ± 0.80	*P* > 0.10	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Rubber mats	% of observations: (1) 4.04 ± 0.58 (2) 3.54 ± 0.58	*P* > 0.10	24 cows	Rushen et al. (2007)
Head position: resting on floor	**Pens & tie-stall**	Video observation	Housing type: (1) Large pens (2) Tie-stall	%/d: (1) 0.65 ± 0.27 (2) 1.90 ± 0.92	*P* = 0.2411	8 cows	Haley et al. (2000)
	Pasture & deep bedded loose housing & tie-stall	Video observation	Housing/stall type: (1) Loose housing: Pasture, milked x2 daily (2) Loose housing: Deep Bedding, milked x2 daily (3) Tie-stall: Concrete floor + 1kg straw, milked x2 daily, no exercise (4) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, no exercise (5) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, exercise	%/total lying time: (1) 6.7 ± 1.1[a] (2) 2.6 ± 0.9[b] (3) 2.5 ± 0.9[b] (4) 3.0 ± 0.9[b] (5) 2.6 ± 0.9[b]	[abcd]*P* < 0.05	24 pairs of twin cows	Krohn and Munksgaard (1993)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	% of total observations: (1) 1.51 ± 0.45 (2) 1.46 ± 0.46	*P* > 0.10	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Front of stall opening: (1) Narrow (2) Wide	% of total observations: (1) 0.67 ± 0.24 (2) 0.30 ± 0.10	*P* > 0.10	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Rubber mats	% of observations: (1) 3.67 ± 2.21 (2) 1.71 ± 2.21	*P* > 0.10	24 cows	Rushen et al. (2007)
Head position: head up	**Pens & tie-stall**	Video observation	Housing type: (1) Large pens (2) Tie-stall	%/d: (1) 54.70 ± 3.28 (2) 37.37 ± 3.85	*P* = 0.0009	8 cows	Haley et al. (2000)

	Pasture & deep bedded loose housing & tie-stall	Video observation	Housing/stall type: (1) Loose housing: Pasture, milked x2 daily (2) Loose housing: Deep Bedding, milked x2 daily (3) Tie-stall: Concrete floor + 1kg straw, milked x2 daily, no exercise (4) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, no exercise (5) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, exercise	frequency / lying hour: (1) 3.2 ± 0.2 (2) 3.7 ± 0.2 (3) 4.0 ± 0.2 (4) 3.4 ± 0.2 (5) 3.8 ± 0.2	$P < 0.05$	24 pairs of twin cows	Krohn and Munksgaard (1993)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	% of total observations: (1) 44.36 ± 1.50 (2) 37.36 ± 1.84	$P = 0.001$	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Front of stall opening: (1) Narrow (2) Wide	% of total observations: (1) 46.81 ± 1.77 (2) 49.10 ± 1.80	$P > 0.10$	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Rubber mats	% of observations: (1) 28.71 ± 6.30 (2) 33.38 ± 6.30	$P = 0.03$	24 cows	Rushen et al. (2007)
Lying flat on side	**Pasture & deep bedded loose housing & tie-stall**	Video observation	Housing/stall type: (1) Loose housing: Pasture, milked x2 daily (2) Loose housing: Deep Bedding, milked x2 daily (3) Tie-stall: Concrete floor + 1kg straw, milked x2 daily, no exercise (4) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, no exercise (5) Tie-stall: Rubber mats + 2kg straw, milked 4x daily, exercise	%/total lying time: (1) 1.6 ± 0.3[a] (2) 0.7 ± 0.2[b] (3) 0.7 ± 0.2[b] (4) 0.6 ± 0.2[b] (5) 0.6 ± 0.2[b]	[abcd]$P < 0.05$	24 pairs of twin cows	Krohn and Munksgaard (1993)
Front leg position: extended	**Pens & tie-stall**	Video observation	Housing type: (1) Large pens (2) Tie-stall	%/d: (1) 4.14 ± 1.65 (2) 5.75 ± 1.65	$P = 0.3218$	8 cows	Haley et al. (2000)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	% of total observations: (1) 2.77 ± 0.76 (2) 2.34 ± 0.86	$P > 0.10$	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Front of stall opening: (1) Narrow (2) Wide	% of total observations: (1) 1.33 ± 0.54 (2) 0.66 ± 0.21	$P > 0.10$	16 cows	Haley et al. (2001)
Front leg position: tucked	**Pens & tie-stall**	Video observation	Housing type: (1) Large pens (2) Tie-stall	%/d: (1) 58.75 ± 11.68 (2) 38.29 ± 3.33	$P = 0.0004$	8 cows	Haley et al. (2000)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	% of total observations: (1) 40.40 ± 1.77 (2) 48.28 ± 1.22	$P = 0.001$	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Front of stall opening: (1) Narrow (2) Wide	% of total observations: (1) 51.02 ± 1.6 0 (2) 54.20 ± 1.79	$P > 0.10$	16 cows	Haley et al. (2001)
Hind leg position: extended	**Pens & tie-stall**	Video observation	Housing type: (1) Large pens (2) Tie-stall	%/d: (1) 11.85 ± 1.55 (2) 8.28 ± 2.76	$P = 0.2710$	8 cows	Haley et al. (2000)

	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	% of total observations: (1) 3.37 ± 1.79 (2) 4.17 ± 1.35	*P* > 0.10	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Front of stall opening: (1) Narrow (2) Wide	% of total observations: (1) 4.94 ± 1.38 (2) 5.95 ± 1.56	*P* > 0.10	16 cows	Haley et al. (2001)
Hind leg position: middle	**Pens & tie-stall**	Video observation	Housing type: (1) Large pens (2) Tie-stall	%/d: (1) 37.72 ± 3.92 (2) 24.88 ± 3.42	*P* = 0.0047	8 cows	Haley et al. (2000)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	% of total observations: (1) 33.51 ± 2.13 (2) 39.39 ± 1.68	*P* = 0.05	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Front of stall opening: (1) Narrow (2) Wide	% of total observations: (1) 39.39 ± 1.68 (2) 38.72 ± 2.29	*P* > 0.10	16 cows	Haley et al. (2001)
Hind leg position: tucked	**Pens & tie-stall**	Video observation	Housing type: (1) Large pens (2) Tie-stall	%/d: (1) 13.31 ± 1.60 (2) 10.88 ± 2.22	*P* = 0.2743	8 cows	Haley et al. (2000)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	% of total observations: (1) 6.29 ± 1.04 (2) 7.07 ± 1.23	*P* > 0.10	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Front of stall opening: (1) Narrow (2) Wide	% of total observations: (1) 8.70 ± 1.85 (2) 10.37 ± 2.38	*P* > 0.10	16 cows	Haley et al. (2001)
Both legs position: extended	**Pens & tie-stall**	Video observation	Housing type: (1) Large pens (2) Tie-stall	%/d: (1) 2.15 ± 0.77 (2) 2.08 ± 1.16	*P* = 0.9622	8 cows	Haley et al. (2000)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	% of total observations: (1) 0.54 ± 0.29 (2) 0.68 ± 0.43	*P* > 0.10	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Front of stall opening: (1) Narrow (2) Wide	% of total observations: (1) 0.31 ± 0.13 (2) 0.13 ± 0.04	*P* > 0.10	16 cows	Haley et al. (2001)
Both legs position: tucked	**Pens & tie-stall**	Video observation	Housing type: (1) Large pens (2) Tie-stall	%/d: (1) 10.04 ± 1.50 (2) 10.43 ± 2.08	*P* = 0.1971	8 cows	Haley et al. (2000)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	% of total observations: (1) 6.14 ± 1.04 (2) 6.92 ± 1.22	*P* > 0.10	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Front of stall opening: (1) Narrow (2) Wide	% of total observations: (1) 8.61 ± 1.85 (2) 10.34 ± 2.37	*P* > 0.10	16 cows	Haley et al. (2001)

[1]Compares the housing environments effect on lying positions

[2]Different letters represents a significant difference between the treatments

Standing behaviours have also been used to evaluate dairy cow welfare (Table 2.11). Study findings have shown that housing type (Haley et al., 2000), stall base (Haley et al., 2001), stall configuration (Tucker et al., 2004; Rushen et al., 2007), and bedding depth and material (Tucker et al., 2003; Tucker and Weary, 2004) can affect the standing behaviours of dairy cows. For example, cows spent more time standing with fewer standing bouts in tie-stalls compared to pens and when on harder bedding material/less bedding compared to softer stall base material/increased bedding (Haley et al., 2000; Haley et al., 2001; Tucker and Weary, 2004; Rushen et al., 2007). This could indicate that cows may not feel as comfortable transitioning between standing and lying due to space restraints or impact of their legs on a harder stall base. Additionally, studies have found that cows with shorter stalls and less bedding spend more time standing with only their front two hooves in the stall (Tucker and Weary, 2004; Tucker et al., 2004). A study by Abade et al. (2015) also found that cows in free-stalls with an alternative design (no neck-rail or stall dividers) resulted in cows spending more time with all four hooves in their stall compared to conventional free-stall design. Thus, cows standing with only their front two hooves in the stall could be an indication that cows are restricted in space at the front of the stall and/or feel uncomfortable standing in the stall due to the hardness of the stall base. lyings could therefore provide some useful insight to the comfort provided to cows at the stall.

Table 2.11 Studies using standing behaviours to measure dairy cow welfare

Cow ease of movement measure	**Stall type/ Housing type**	Method of Measurement	Treatments	Comparison[1]	Significance	n	Reference
Total standing time	**Free-stall**	Video observation	Bedding: (1) Deep bedded sawdust (2) Deep bedded sand (3) Geotextile mattress covered with 2-3 cm of sawdust	h/d: (1) 0.4 ± 0.08[a] (2) 0.4 ± 0.10[a] (3) 0.6 ± 0.08[b]	$^{abcd}P \leq 0.05$[2]	12 cows	Tucker et al. (2003)
	Pens & tie-stall	Video observation	Housing type: (1) Large pens (2) Tie-stall	h/d: (1) 8.53 ± 0.90 (2) 12.80 ± 1.05	$P = 0.0006$	8 cows	Haley et al. (2000)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	h/d: (1) 12.87 ± 0.42 (2) 11.04 ± 3.68	$P = 0.01$	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Front of stall opening: (1) Narrow (2) Wide	h/d: (1) 10.67 ± 0.42 (2) 9.98 ± 0.45	NS[3]	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Rubber mats	h/d: (1) 14.98 ± 0.29 (2) 13.67 ± 0.29	$P = 0.04$	24 Holstein cows	Rushen et al. (2007)
	Free-stall	Video observation	Bedding: (1) Pasture mat with 0 kg sawdust (2) Pasture mat with 1 kg sawdust (3) Pasture mat with 7.5 kg sawdust	min/d: (1) 106 +30.9/-24.0 (2) 85 +24.5/-19.0 (3) 70 +19.9/-15.5	$P = 0.03$[4]	10 cows	Tucker and Weary (2004)
	Free-stall	Video observation	Stall width: (1) Narrow (112 cm) (2) Wide (132 cm)	min/d: (1) 275 ± 15.2 (2) 228 ± 15.2	$P = 0.04$	15 cows	Tucker et al. (2004)
	Free-stall	Video observation	Stall length: (1) Short (229 cm) (2) Long (274 cm)	min/d: (1) 264 ± 15.2 (2) 239 ± 15.2	$P = 0.26$	15 cows	Tucker et al. (2004)
Frequency of standing	**Pens & tie-stall**	Video observation	Housing types: (1) Large pens (2) Tie-stall	n/d: (1) 15.29 ± 1.34 (2) 9.75 ± 1.07	$P = 0.0014$	8 cows	Haley et al. (2000)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	n/d: (1) 10.77 ± 0.93 (2) 14.84 ± 1.15	$P = 0.001$	16 cows	Haley et al. (2001)
	Tie-stall	Video observation	Front of stall opening: (1) Narrow (2) Wide	n/d: (1) 14.14 ± 0.91 (2) 15.88 ± 1.40	NS	16 cows	Haley et al. (2001)
Standing bout duration	**Pens & tie-stall**	Video observation	Housing type: (1) Large pens (2) Tie-stall	min/bout: (1) 36.14 ± 5.31 (2) 86.70 ± 13.23	$P = 0.0015$	8 cows	Haley et al. (2000)
	Tie-stall	Video observation	Stall base: (1) Concrete (2) Mattress	min/d: (1) 80.14 ± 7.53 (2) 48.35 ± 3.68	$p = 0.001$	16 Holstein cows	Haley et al. (2001)
	Tie-stall	Video observation	Front of stall opening: (1) Narrow stall (2) Wide	min/d (1) 48.71 ± 4.11 (2) 43.11 ± 4.79	NS	16 Holstein cows	Haley et al. (2001)

	Tie-stall	Video observation	Stall base: (1) Concrete (2) Rubber mats	min/d: (1) 118.23 ± 12.31 (2) 76.58 ± 12.31	P = 0.02	24 Holstein cows	Rushen et al. (2007)
Standing with only the 2 front hooves in the stall	**Free-stall**	Video observation	(1) Conventional stall (with neck-rail and metal stall dividers) (2) Alternative stall (no neck-rail or stall dividers other than a wooden board protruding a little above the lying surface)	ave. across trt.[5]: 1.2 h/d	P = 0.41	48 cows	Abade et al. (2015)
	Free-stall	Video observation	Bedding: (1) Pasture mat with 0 kg sawdust (2) Pasture mat with 1 kg sawdust (3) Pasture mat with 7.5 kg sawdust	min/d: (1) 58 +26.6/-17.7 (2) 51 +22.8/-15.8 (3) 38 +16.9/-11.7	P = 0.03	10 cows	Tucker and Weary (2004)
	Free-stall	Video observation	Stall width: (1) Narrow (112 cm) (2) Wide (132 cm)	min/d: (1) 168 ± 12.6 (2) 136 ± 12.6 min/d	P = 0.07	15 cows	Tucker et al. (2004)
	Free-stall	Video observation	Stall length: (1) Short (229 cm) (2) Long (274 cm)	min/d: (1) 173 ± 12.6 (2) 131 ± 12.6	P = 0.02	15 cows	Tucker et al. (2004)
Standing with all 4 hooves in the stall	**Free-stall**	Video observation	(1) Conventional stall (with neck-rail and metal stall dividers) (2) Alternative stall (no neck-rail or stall dividers other than a wooden board protruding a little above the lying surface)	h/d: (1) almost never (2) 0.6	P < 0.001	48 cows	Abade et al. (2015)
	Free-stall	Video observation	Stall base: (1) Pasture mat with 0 kg sawdust (2) Pasture mat with 1 kg sawdust (3) Pasture mat with 7.5 kg sawdust	min/d: (1) 27 +8.4/-6.4 (2) 22 +7.1/-5.4 (3) 21 +6.6/-5.0	P = 0.55	10 cows	Tucker and Weary (2004)
	Free-stall	Video observation	Stall width: (1) Narrow (112 cm) (2) Wide (132 cm)	min/d: (1) 106 ± 10.2 (2) 93 ± 10.2	P = 0.38	15 cows	Tucker et al. (2004)
	Free-stall	Video observation	Stall length: (1) Short (229 cm) (2) Long (274 cm)	min/d: (1) 91 ± 10.2 (2) 108 ± 10.2	P = 0.22	15 cows	Tucker et al. (2004)

[1]Compares the housing environments effect on standing behaviours in the studies

[2]Different letters represents a significant difference between the treatments

[3] NS = not significant with a *P*-value greater than 0.05

[4]*P*-values are a linear contrast

[5]Ave. = average and trt. = treatment

2.5 Summary

Overall, this literature review shows that tie-rail placement could have an effect on dairy cow welfare such as injuries, lameness, standing and lying behaviours, and stall and cow cleanliness. However, studies have found conflicting results for the ideal tie-rail placement. Previous studies investigating the effects of tie-rail placement on cow welfare were epidemiological, making it difficult to isolate the effects of the tie-rail placement alone due to possible interactions with other factors such as stall dimensions and management practices. This may explain some of the conflicting results. Additionally, certain measures of dairy cow welfare that may be affected by tie-rail placement, such as the lying and rising ability of dairy cows, have yet to be evaluated. Thus, there is a need to study tie-rail placement in a controlled environment to determine the ideal tie-rail placement and its direct effect on welfare outcome measures such as clinical signs, production, cleanliness, and cow ease of movement.

CONNECTING TEXT

In chapter 2 we reviewed the functions, recommendations and effects of tie-rail in tie-stall and neck-rail and feed-rail in free-stall. We observed that there are some conflicting results between what studies have found for ideal tie-rail and neck rail placements. Additionally, conflicting results were even found between epidemiological studies looking at risk factors associated with tie-rail placement on tie-stall farms, leading to the possibility that other stall dimensions and management practices may play a role in these conflicting results. Also, certain outcome measures of dairy cow welfare such as the effect tie-rails have on lying-down and rising ability have yet to be tested, making it difficult to determine what the ideal tie-rail placement should be. Thus, there is a need for an experimental study to determine the ideal tie-rail height and forward position combination, since in chapter 2 we found that both tie-rail height and forward position have an effect and conflicting outcomes on dairy cow welfare. In order to develop a new recommendation for tie-rail placement we will be studying outcome measures of welfare such as clinical signs, stall and cow cleanliness, production, and cow ease of movement measures, which were reviewed in chapter 2. The next chapter (chapter 3) will present an experiment conducted to determine an ideal tie-rail placement by observing outcome measures of welfare.

CHAPTER 3. THE EFFECT TIE-RAIL PLACEMENTS FOLLOWING THE NATURAL NECK LINE OF COWS WHEN EATING AND RISING HAVE ON THE WELFARE OF DAIRY COWS HOUSED IN TIE-STALL BARNS

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Draft manuscript to be submitted to the Journal of Dairy Science

3.1 Abstract

Our objective was to develop new recommendations for tie-rail placement combining both vertical and horizontal positions to improve dairy cow welfare. Four treatments were tested: two new tie-rail positions that followed the natural neck line of cows when feeding and rising (Neckline1, Neckline2), Current Recommendation, and the tie-rail position most commonly found on Québec farms (Common on Farm). All other stall dimensions followed current recommendation based on cow size. Forty-eight cows, blocked by parity and stage of lactation were randomly allocated to a treatment for 10 weeks. Live scoring was performed weekly to evaluate: injury, cow and stall cleanliness, bedding quantity, and body condition. Lameness scoring was performed weekly through video observation. Milk yield was recorded at each milking and milk samples were collected weekly to evaluate milk components. Feeding/rumination time was recorded continuously using ear-mounted activity data loggers. Daily lying time, lying bout frequency, and duration of lying bouts were continuously recorded using leg mounted accelerometers. Cows were recorded 1 d/wk by overhead cameras and 6 lying and rising events were evaluated per recording.

The tie-rail placements tested did not affect cow and stall cleanliness, bedding quantity, body condition, lameness, milk yield and components, feeding/rumination time, and resting behaviour. Current Recommendation (difference from wk 0: +0.9) increased proximal neck injuries compared to Neckline2 (+0.1). Neckline2 (+0.8) and Neckline1 (+0.5) increased medial neck injuries compared to the Current Recommendation (-0.1). All treatments showed a decrease in average lying intention time (-5.9 s/event), lying-down time (-1.1 s/event), contact with stall during lying (-32.5%) and slipping during lying (-9.4%). All treatments decreased backwards movement on knees during rising (-10.8%), contact with tie-rail during rising (-14.3%) and overall abnormal rising (-15.7%). Although lying and rising ability improved over time, abnormal lying and rising were still highly prevalent in the long-term.

Our results show that dairy cows are limited in their ability to move within their environment without coming in contact with the tie-rail and divider bars. This warrants further research to determine the benefits of housing that provide fewer obstacles through the elimination of some stall hardware and increase an individual cow's space through larger or longer stalls.

3.2 Introduction

There is an increasing public concern for dairy cows to be able to exhibit natural behaviour (Prickett et al., 2010), which is also an important issue for cows themselves as housing systems that limit cows' natural behaviour have been associated with poor outcome measures of welfare. For example, long lying time and short lying bouts have been associated with an increased risk of lameness (Ito et al., 2010; Westin et al., 2016). Furthermore, cows have a specific sequence of events that they perform when they are lying and rising. When the environment is restrictive (e.g., space availability, hardware, lack of cushioning, etc.) cows show abnormal durations of lying and rising motion, which are indications of discomfort and have been associated with injury and/or lameness (Lidfors, 1989; Krohn and Munksgaard, 1993; Dippel et al., 2009). The risk of lameness increases with an increase in abnormal lying behaviours or the presence of an obstacle (brisket board and/or rail) impending head lunge space (Dippel et al., 2009). Cows often collide with housing equipment during lying and rising events (Plesch et al., 2010). Stalls should be configured to allow cows to exhibit their natural behaviours, allowing for proper lying and rising motions.

Stall configuration is associated with several outcome measures of welfare, such as abnormal behaviour, injury, lameness and cleanliness (Tucker et al., 2005; Zurbrigg et al., 2005; Bernardi et al., 2009; Kielland et al., 2010; Potterton et al., 2011; Bouffard et al., 2017). However, some differences between results may be due to the fact that tie-rails serve an additional purpose of separating cows from feed; a function commonly carried out by feed-rails in free-stalls. Studies suggest that both tie-rail and feed-rail placements affect neck injuries (Zurbrigg et al., 2005; Kielland et al., 2010; Heyerhoff et al., 2014; Bouffard et al., 2017). When evaluating different tie-rail, neck-rail and feed-rail placements, studies often evaluate the rails' forward position and height separately. Results from previous studies suggest that increasing the forward position of tie-rails and neck-rails may increase lying bout frequency and decrease the risk of lameness and neck, hock, and knee injuries, while reducing stall and cow cleanliness (Zurbrigg et al., 2005; Bernardi et al., 2009; Potterton et al., 2011; Bouffard et al., 2017). However, a study by Nash et al. (2016) performed on tie-stalls found that the probability of hock injury increased when tie-rails were positioned further forward. Therefore, there are conflicting results when considering an increase in tie-rail forward position. Results for ideal tie-rail, neck-rail, and feed rail heights are also variable. Zurbrigg et al. (2005) found that mid-range heights for tie-rail placement resulted in an increase in neck injuries. Similarly, recent experiments on feed-rail placement have found that increasing feed-rail height may reduce neck injuries (Kielland et al., 2010; Heyerhoff et al., 2014). However, Bouffard et al. (2017) found that when tie-rails were at the current recommendation or higher there was an increased risk of neck, hock and knee injuries and lameness. Thus, there are conflicting results for ideal tie-rail height position. Additionally, the results from Bouffard et al. (2017) suggest that the current recommendation for tie-rail height put the animal at risk of injury and lameness.

The current recommendations have been based on the cows' body dimensions (Anderson, 2014b). For tie-rails, the current recommendation has been split into two different aspects, tie-rail height and tie-rail forward position (DFC - NFACC, 2009; Anderson, 2014b). However, there seems to be conflicting results when evaluating the tie-rail height and forward position alone. Thus, the purpose of this study was to examine combinations of tie-rail height and forward position to determine the ideal tie-rail position for cows housed in tie-stall systems. To do this we looked at two tie-rail positions that follow the neck line of cows when they are feeding and when they are rising. This was done because it is hypothesized that dairy cows often come in contact with the tie-rail when they are rising and often push on the tie-rail during feeding (Bouffard et al., 2017). Therefore, the objective of this study was to evaluate two different tie-rail height and forward position combinations and compare them to the currently recommended tie-rail position and the position commonly found on farms in Quebec.

3.3 Materials and methods

3.3.1 *Cows and treatments*

This experiment was conducted at McGill University's Macdonald campus tie-stall barn (Quebec, Canada). Forty-eight Holstein lactating cows were enrolled for 10 weeks over two separate start dates (24 cows per start date): July 25 to October 3, 2016 (considered as summer season) and October 10 to December 19, 2016 (fall season). The final dataset included data from 45 cows. One cow was removed from the trial due to metabolic disease (second week of enrollment) and two other cows were removed due physical injury unrelated to tie-rail placement (eighth week of enrollment).

Within each start date the cows were divided into 6 blocks based on parity (primiparous or multiparous), days in milk (DIM; early: 0 – 100 d, mid: 101 – 200 d or late: 201 – 305 d) and location in the barn (row 1 or 2). The cows within each block were then randomly allocated to one of four treatments (12 cows per treatment). Treatment 1: **Current Recommendation** was at 121.9 cm from the stall base and 35.6 cm from the manger wall and was used as a control treatment (Canadian Dairy Code of practices; DFC - NFACC, 2009). Treatment 2: **Common on Farm** was at 121.9 cm from the stall base and 17.8 cm from the manger wall, and was the position closest to what is most commonly found on farms in Quebec (Bouffard et al. 2017). Two new positions were developed with the aim of improving cow's ease of movement and reducing contact with the tie-rail by following the neck line of cows while they are rising and eating. Treatment 3: **Neckline1** had the same forward position as Common on Farm treatment at 17.8 cm forward from the manger wall, but was positioned lower (111.8 cm) relative to the stall base. Treatment 4: **Neckline2** had the same forward position as Current Recommendation at 35.6 cm forward from the manger wall, but was positioned lower (101.6 cm) relative to the stall base.

3.3.2 Housing and management

Cows were housed in two locations in the barn (i.e. two separate rows of tie-stalls facing the barn wall). The tie-stall dimensions were all based on the cow's size (average rump height being 153.4 ± 4.22 cm and average hook bone width being 66.4 ± 4.20 cm), and the stalls were designed to fit each cow's size within ± 5.08 cm of current recommendation (DFC - NFACC, 2009; Anderson, 2014b). All the stalls had new rubber mats (KKM longline; Distribution Multi-Mat, Inc. Ste-Cécile-de-Milton, QC, Canada) which were installed a week before the first trial start date. A small layer of wood shavings (less than 2 cm) was added on top of the new rubber mats every morning. Stall base and bedding compressibility was determined by measuring two stalls per row once during the trial using a 10 kg Clegg hammer (Clegg impact soil tester; Lafayette Instrument Company, Lafayette, IN, United States; Fulwider and Palmer, 2004) following the protocol validated for tie-stall use (Villettaz Robichaud et al., unpublished data). The average stall base and bedding compressibility was 5.18 CIV/H (Clegg impact value/weight of Clegg hammer). Hoof trimming was carried out for all cows two months before the first start date and one week before the second start date.

General management at the barn was not altered for cows enrolled in the experiment. The stalls and gutters were scraped continually by barn staff from 05:00 until 21:00. Cows were milked twice daily at the tie-stall from 05:00 to 07:00 and 17:00 to 19:00. Cows were fed a total mixed ration 4 times a day, with feed pushed closer to cows approximately 6 times per day. Water was available ad libitum from self-filling water bowls located intermittently between each stall (two cows shared one water bowl).

3.3.3 Measures

3.3.3.1 *Injury scoring*

Injury scores were recorded once per week using a visual scoring chart by a trained observer, who had received two weeks of training. Seventeen different locations spanning 4 areas of the cows' body (neck, side, back legs and front legs; Figure 3.1) on both the left and right sides of the cows' body were scored for injury. The injury scoring method was adapted from Gibbons et al. (2012) and Brenninkmeyer et al. (2016). Individual injury type was recorded and then categorized into final scores based on degree of severity: 0 = no injury, 1 = hair loss and/or white scab, 2 = bald spot and/or minor swelling, 3 = red scab and/or medium swelling and 4 = lesions and/or major swelling (Table 3.1). If there were multiple injury types in one location, the most severe injury type observed was used to categorize the injury score. At the beginning, middle and end of the 10-week period, interobserver (overall average Kw = 0.76 across injury locations) and intra-observer (overall average Kw = 0.83 across injury locations) repeatability were calculated.

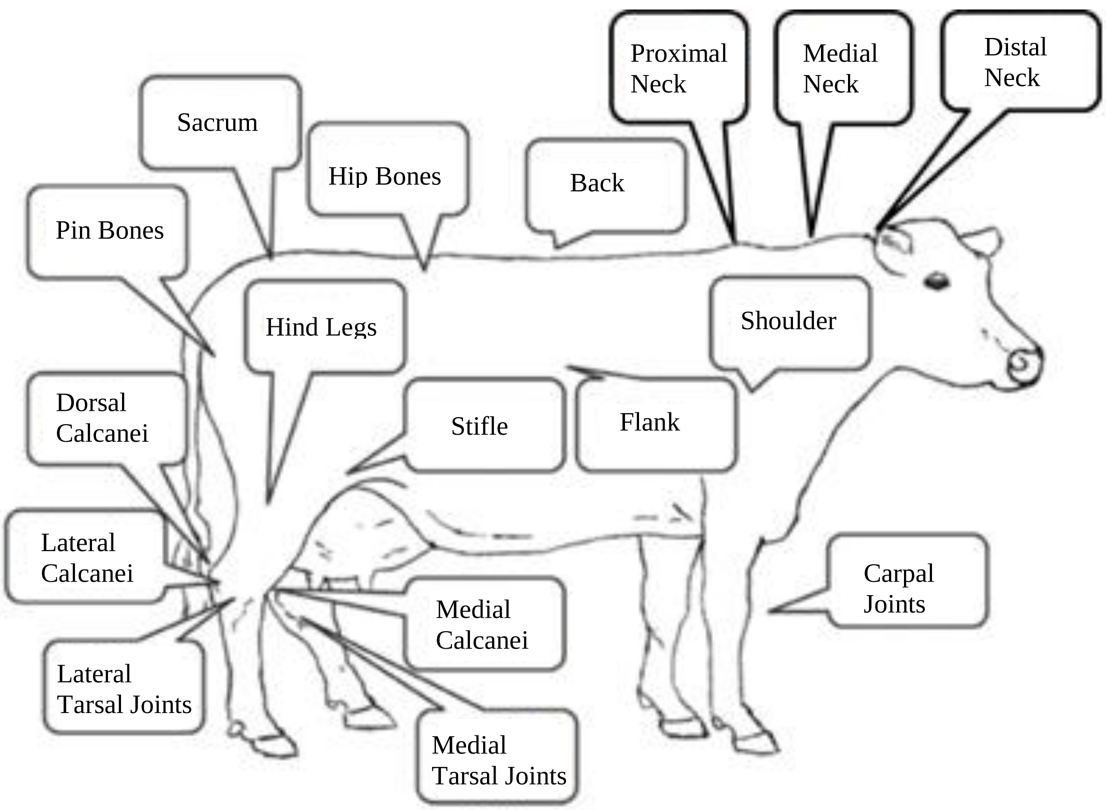


Figure 3.1. Indicates areas that were assessed for injury. The neck area includes proximal, medial and distal neck. The side area includes the shoulder, back, flank, hip bones, sacrum and pin bones. The back leg area includes the hind leg, stifle, lateral calcanei, dorsal calcanei, medial calcanei, lateral tarsal joints (hocks) and medial tarsal joints. The front leg area includes carpal joints (knees). Figure adapted from Brenninkmeyer et al. (2016).

Table 3.1. The severity score for individual injury types used to evaluate each location on the cows' body

Severity score	Injury type	Units	Description
0	No problems	Yes or No	No broken hair, bald spots, scabs, lesions or swelling
1	Broken hair	Yes or No	Hair is split or thinning
	Scabs: white and dry	Yes or No	White crusty skin, indicating a nearly healed wound (feels rough, like a scab)
2	Hair loss/Bald spot	Yes or No	No hair present
	Minor swelling	Yes or No	Observer can feel that the area has an accumulation of fluid (area feels squishy, not firm, but not yet visually larger (< 1 cm))
3	Scabs: red and/or wet	Yes or No	Red crusty skin or red wet skin (if scab was pulled off it would bleed, indicating a healing wound)
	Medium swelling	Yes or No	Observer can feel that the area has an accumulation of fluid and can see a slight enlargement in that area (1-2.5 cm)
4	Lesion/Open wound	Yes or No	Fresh or dry blood is visible (dry blood won't be as thick as a scab and could be removed with cleaning)
	Major swelling	Yes or No	Observer can feel area has an accumulation of fluid and the area looks visually larger and rounded (> 2.5 cm)

3.3.3.3 *Lying and rising events*

Lying and rising events were scored on weeks 1, 2, 3, 6, and 9 for start 1 and weeks 1, 2, 3, 6, and 10 for start 2 through observation videos by three trained observers. Observers used the video recordings from ceiling cameras centered above each stall, 338 cm above the floor (Smart Turret 2.8, Hikvision Digital Technology Co., Ltd., Hangzhou, China; 720p at 8 frames per s). The methodology used has been validated and was described in Zambelis et al. (2018a). For each cow, six lying and rising events (four during the day and two at night) were randomly selected from a 24 h period to be scored each week. Averaging the scores from 4 daytime events and 2 night-time events was sufficient to yield a strong correlation with the full 24 h averages for each indicator of rising and lying-down abnormality (rising: r = 0.95; lying-down: r = 0.90; Zambelis et al., 2018a). Eight indicators of lying ability were observed: duration of intention movements before lying down, duration of lying motion, contact with the stall bars, attempts to lie down, hind quarter stepping, slipping, dog sitting while lying down and lying on the left or right (Table 3.2). Six indicators of rising ability were examined: duration of rising motion, contact with tie-rail, backward movement on carpal joints (knees), delayed rising, attempts at rising, and horse rising (Table 3.3). Summary parameters were created as additional indicators of rising and lying-down abnormality to classify each event as normal (0) or abnormal (1) based on the presence of at least one abnormal behaviour. Abnormal lying-down behaviours included: attempts to lie down, hind quarter stepping, slipping and dog sitting. Abnormal rising behaviours included: contact with tie-rail, backwards movement on knees, delayed rising, attempts of rising and horse rising. Interobserver (across lying behaviours: Kw = 0.96; across rising behaviours: Kw = 0.93) and intra-observer (across lying behaviours: Kw = 0.99; across rising behaviours: Kw = 0.96) repeatability was performed.

Table 3.2. Behavioural indicators for lying down events[1]

Indicators	Units	Description
Intention movements before lying down (phase 1 of lying down)	s/event	Repeated ground sniffing with sweeping movements without lying down* Beginning: when sniffing starts Ends: when phase 2 begins *Should be continuous beginning to end (head of cow should be down for the duration of phase 1)
Duration of lying down motion (phase 2 of lying)	s/event	Start of motion: cow descends to one foreleg End of motion: whole body touches the ground; body is stable

Contact with the stall bars	Yes or no	Cow comes into contact with dividers and/or tie-rail during lying down motion
Attempts of lying down	Number of attempts	Cow stands up after starting lying down movement (goes on carpal joints and then back up onto hooves)
Hind quarters stepping	Yes or no	When on carpal joints, cow makes multiple stepping motions with hindquarters before lying down completely (≥ 3 sec)
Slipping	Yes or no	Cow's front legs slip before descending onto carpal joints
Dog sitting	Yes or no	Cow lies down with hindquarters first and then onto carpal joints
Lying down on left or right	Left or Right	Direction the hind legs point when cow is lying down (based on technician viewing cow from above)

[1]following Zamblis et al. (2018b)

Table 3.3 Behavioural indicators for rising events[1]

Indicators	Units	Description
Duration of rising motion	s/event	Start of motion: cow is in sternal position to propel itself forward End of motion: cow gathers its forelimbs side by side on the stall bed
Contact with tie-rail	Yes or no	During the rising motion, cow's head or neck touches the tie-rail (shock, impact)
Backward movement on carpal joints (knees)	Yes or no	When resting on carpal joints, cow moves its front leg(s) backwards before or after propelling itself
Delayed rising	Yes or no	Cow rests on carpal joints for > 10 s
Attempts of rising	Number of attempts	Cow propels itself forward from sternal position without successfully rising; can appear as a forward and back motion
Horse rising	Yes or no	Cow gets up first with front legs, then with hind legs

[1]following Zamblis et al. (2018b)

3.3.3.4 Resting behaviour

Resting behaviour was automatically recorded 7 days per week using leg mounted accelerometers (HOBO Pendant G Acceleration Data Loggers, Onset Computer Corporation, Pocasset, MA, USA), which have been previously validated for use in tie-stall cows (Vasseur et al., 2012). The data loggers were placed on the hind leg of each cow using vetwrap (CoFlex® Vet; Andover Healthcare, Inc. MA, Salisbury, USA) and switched weekly to avoid skin injury. Daily duration of total lying time, average number of lying bouts, and average duration of lying bouts were computed per week using Excel macros (Microsoft Corp., Redmond, WA).

3.3.3.5 *Cow and stall cleanliness and bedding quantity*

Cow and stall cleanliness and bedding quantity scores were performed according to standard operating procedures (SOPs) described in Vasseur et al. (2015), which can be found on the Canadian Dairy Research Portal (https://www.dairyresearch.ca/cow-comfort.php#self). Cow cleanliness was scored for each cow once per week after morning milking by a trained observer. Three areas of the cows were scored on a scale of 0-3 (lower back leg, back portion of udder, and flank), and each week the lower back leg and flank were scored on alternating sides (leg without activity monitor was scored). Scores were categorized as either clean (0 or 1) or dirty (2 or 3). Repeatability was checked at the beginning, middle and end of the 10-week period interobserver (overall average % agreement = 98.0) and intra-observer (overall average % agreement = 97.0). Stall cleanliness was scored once per week for each cow before the stalls were cleaned/scrapped in the morning by three trained observers on a scale 0-4 and categorized as clean (score 0-1) or dirty (score 2-4). Repeatability was checked 3 times across the study (interobserver: Kw = 0.80; intra-observer: Kw = 0.71). Bedding quantity was scored once per week for each cow before the stalls were cleaned/scrapped in the morning and categorized as either little or deep bedding by three trained observers. Little bedding was classified as less then 2 cm of bedding and deep bedding was classified as greater than 2 cm of bedding. Repeatability was checked 3 times across the study (interobserver: overall average Kw = 0.76; intra-observer: overall average Kw = 0.88).

3.3.3.5 *Lameness, body condition scoring and feeding/rumination time*

Lameness was scored once per week for each cow through video observation by three trained observers using stall lameness scoring (SLS) method as described by Palacio et al. (2017) and Gibbons et al. (2014), adapted from Leach et al. (2009). Cows were observed standing from three positions for 10 s at a time. The observer looked for four different indicators of lameness. 1. weight shift (shift): regular, repeated shifting of weight from one hoof to another, defined as lifting each hind hoof completely off the ground at least twice and landing in the same location. 2. standing on edge (edge): the cow places one hoof or both at the edge of the stall while standing. 3. uneven weight bearing when standing (rest): the cow repeatedly rests one foot more than the other, indicated by raising a part or the entire hoof off the ground. The cow was then encouraged to move from side to side, during which the fourth behaviour was observed: 4. uneven weight bearing during movement (uneven): uneven weight bearing between the left and right feet when the cow moves from side to side. A cow was considered lame when 2 or more of these behaviours were observed. On a weekly basis, intra-observer (average overall Kw = 0.77) and inter-observer (average overall Kw = 0.79) repeatability was performed.

Body condition score (BCS) was assessed once per week for each cow by a trained observer using an up to 5-point scoring system with increments of 0.25, where a score of 2 or below categorized the cow as severely under-conditioned and a score above 2 categorized the cow as adequately conditioned (Vasseur et al., 2013). Interobserver (overall average Kw = 0.63) and intra-observer (overall average Kw = 0.66) reliability was performed at the beginning, middle and end over a 10-week period.

Rumination and feeding time were recorded continuously over the duration of the trial for 24 cows equally distributed across treatments using ear-mounted activity data loggers (Cowmanager SensOor, Agis Automatisering, Hermelen, The Netherlands) that had previously been used in tie-stall cows by Ouellet et al. (2016). A validation study of the logger by Zambelis et al. (2018b) found that the correlation strength between visual observation and the data loggers was low for time spent ruminating (r = 0.27) and eating (r = 0.69) separately; however, combining the two indicators was found to be an accurate representation of total time spent feeding and ruminating (r = 0.83). Therefore, we combined the weekly average percentage of time spent ruminating and percentage of time spent eating per hour to obtain the weekly average percentage of time cows spent feeding/rumination (% of time/h).

3.3.3.6 Production measures

Milk yield was recorded at each milking by the automated program Delpro software 1.5. Daily milk yields were averaged over 7 days to determine the average milk yield per week for each cow. Milk samples were collected once per week for each cow during the evening milking and then again during the morning milking of the next day. Evening and morning milking samples were then mixed together to give a representative sample. The milk samples were then analyzed by the Dairy Production Centre of Expertise, Valacta Inc. (Ste-Anne-de-Bellevue, Québec, Canada) to determine milk components. The milk components recorded were: fat (kg/d), protein (kg/d), lactose (kg/d), total solids (kg/d), somatic cell count (SCC; 000/ml), urea (mg/dl), beta-hydroxybutyrate (BHB; mmol/l), short chain fatty acid (SCFA; %), medium chain fatty acid (MCFA; %), and palmitic acid (C16:0; %). DeNovo fatty acids (DeNovo FA; %) was then calculated by means of the following equation: DeNovo FA = SCFA + MCFA – C16:0.

3.3.4 *Statistical analysis*

Comparing the different tie-rail treatments to Current Recommendation (control) over time was analyzed using a mixed model in SAS 9.4 (SAS Institute Inc. (2012), Cary, NC, USA):

$y_{ijknm} = \mu + trt_i + start_j + block_{jk} + cow_{ijkn} + week_m + e_{ijknm}$

Where: y_{ijknm} was the dependent variable; the outcome measure of the n^{th} cow from the k^{th} block (parity, DIM and location in the barn) and the j^{th} start date on the combination of the i^{th} tie-rail position and m^{th} week. Trt_i was the fixed effect of the i^{th} tie-rail position. $Start_j$ was the fixed effect the j^{th} start date. $Block_{jk}$ was the fixed effect of k^{th} parity, DIM and location in the barn from the j^{th} start date. Cow_{ijkn} was the random effect of the n^{th} cow from the j^{th} start date and the k^{th} block on the i^{th} tie-rail position treatment. $Week_m$ was the fixed effect of the m^{th} week. e_{ijknm} was the random residual associated with the outcome measure of the n^{th} cow from j^{th} start date and k^{th} block on the combination of the i^{th} tie-rail position treatment and the m^{th} week.

To determine the short-, mid- and long-term effects of tie-rail placements, we analysed the average of weeks 1, 2 and 3 to represent short-term, week 6 represented mid-term, and the average of weeks 8, 9 and 10 represented long-term. The difference among treatments was calculated by comparing the Common on Farm, Neckline1 and Neckline2 tie-rail treatments to the Current Recommendation (control treatment) using Dunnett's adjustment to adjust for multiple comparisons on a per term basis. To analyze the difference between the terms, a Scheffé adjustment was used to adjust for multiple-comparisons.

The score difference from week 0 was used as the outcome measure for lameness and injury because they were not accounted for during cow selection in our experimental design. Additionally, the average injury score from the left and right sides of the cow's body was taken to represent the score for that cow's body part per week. For instance, the injury scores of the right and left shoulders were averaged and then used in the statistically analysis to represent the overall injury score of the shoulder.

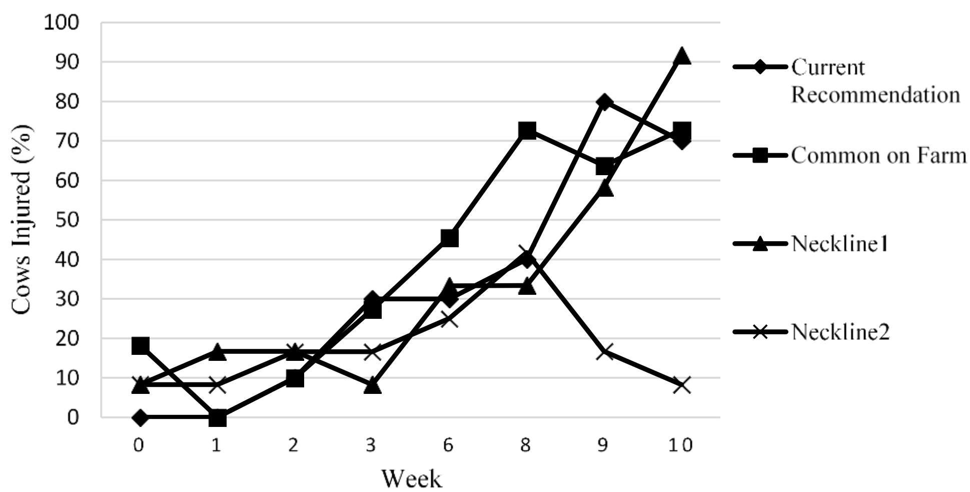
The percentage of clean cows, clean stalls and deep bedding were averaged per treatment per week and used as the outcome measures for cow cleanliness, stall cleanliness and bedding quantity.

3.4 Results

3.4.1 *Neck injuries*

We found that proximal neck injury scores were lower during the long-term period for cows in Neckline2 (score difference from week 0: +0.06 ± 0.15) compared to cows in Current Recommendation (control treatment; +0.9 ± 0.16; $P \leq 0.05$; Table 3.4). However, medial neck injury scores during the mid-term period increased for cows in Neckline2 (+0.4 ± 0.20) compared to cows in Current Recommendation (-0.3 ± 0.22; $P \leq 0.05$). During the long-term period medial neck injury scores increased for both Neckline2 and Neckline1 (+0.8 ± 0.16 and +0.5 ± 0.16) compared to cows in Current Recommendation (-0.1 ± 0.18; $P \leq 0.05$). An overall increase over time in proximal neck injury scores (short-term: +0.05 ± 0.077 and long-term: +0.7 ± 0.077; $P \leq$ 0.05) and medial neck injury scores (short-term: -0.03 ± 0.084 and long-term: +0.3 ± 0.089; $P \leq$ 0.05) was found for all cows, regardless of tie-rail treatment. Figure 3.2 shows the prevalence of proximal and medial neck injuries per treatment over time.

A) Proximal Neck Injury Prevalence



B) Medial Neck Injury Prevalence

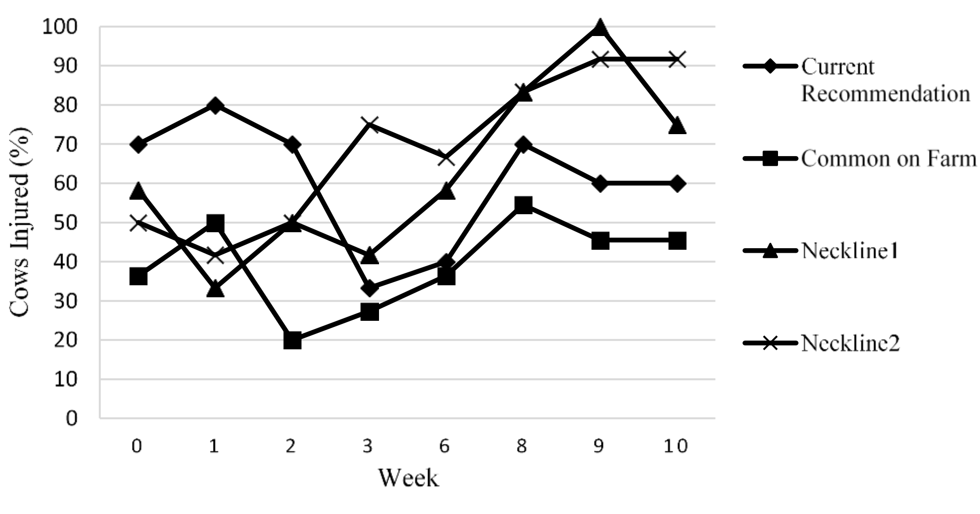


Figure 3.2. The prevalence of cows with proximal (A) and medial (B) neck injuries for Current Recommendation (control), Common on Farm, Neckline1 and Neckline 2 treatments over 10 weeks.

Distal neck injury scores were not different between the tie-rail treatments and Current Recommendation or over time. The prevalence of distal neck injuries was 0% at week 0 and 10.

3.4.2 *Side injuries*

Back injury scores decreased during the long-term period for Neckline2 cows compared to cows in Current Recommendation (Table 3.4). The prevalence of back injuries for Current Recommendation, Common on Farm, Neckline1, and Neckline2 was: 5%, 0%, 12.5% and 16.7%, respectively, for cows injured at week 0, and 5%, 0%, 4.2% and 0%, respectively, for cows injured at week 10. Hip bone injury scores decreased during the long-term period for Neckline1 cows (-0.4 ± 0.10) compared to cows in Current Recommendation (+0.02 ± 0.12; $P \leq 0.05$). The prevalence of hip bone injuries for Current Recommendation, Common on Farm, Neckline1 and Neckline2 was: 10%, 13.6%, 29.1% and 4.2%, respectively, at week 0 and 10%, 0%, 12% and 4.2% at week 10. No significant differences were found for injury scores on the shoulder, flank, sacrum and pin bone between the different tie-rail treatments and Current Recommendation or over time.

3.4.3 *Back leg injuries*

The lateral tarsal joint, commonly known as the hock, and the dorsal calcanei injury scores for the various tie-rail treatments were not different when compared to Current Recommendation; however, there was a significant increase in injury scores for both locations over time (Table 3.4). Across all tie-rail treatments lateral tarsal joint injury scores increased during the mid-term period (score difference from week 0: +0.5 ± 0.11) compared to short-term period (+0.2 ± 0.10; $P \leq 0.05$). For all tie-rail treatments, the injury prevalence of lateral tarsal joint injuries was 100% at week 0 and 100% at week 10, but the severity of injuries increased and then decreased over time. Dorsal calcanei injury scores increased during the long-term period (+0.08 ± 0.12) compared to the short-term period (-0.2 ± 0.12; $P \leq 0.05$). The prevalence of dorsal calcanei injuries for Current Recommendation, Common on farm, Neckline1 and Neckline2 was 58.9%, 45.5%, 45.8% and 50%, respectively, at week 0, and 65%, 36.4%, 64.2% and 41.7% at week 10. Hind leg, stifle, lateral calcanei, medial calcanei and medial tarsal joint injury scores did not differ significantly between the different tie-rail treatments and Current Recommendation, or over time.

3.4.4 *Front leg injuries*

We found no difference between injury scores at the carpal joint, commonly known as knee, when comparing the various tie-rail treatments to Current Recommendation and over time (Table 3.4). The prevalence of carpal joint injuries for Current Recommendation, Common on Farm, Neckline1 and Neckline2 was 95%, 86.4%, 95.8% and 100%, respectively, at week 0, and 100%, 95.5%, 100% and 100% at week 10.

Table 3.4. Injury scores (score difference from week 0) for 17 different locations on the body, grouped by neck, side, back leg and front leg, for Current Recommendation (control), Common on farm, Neckline1 and Neckline2 treatments during the short-, mid- and long-term periods[1]

	Periods[2]			Treatments[3]				
Injury Location	Term	LSmean[4]	SE	Control	Common on Farm	Neckline 1	Neckline 2	SE[5]
Neck								
Proximal	Short	0.05^{x}	0.077	0.12	-0.01	0.06	0.06	0.153
	Mid	0.36^{xy}	0.087	0.49	0.53	0.33	0.08	0.173
	Long	0.66^{y}	0.077	0.89^{a}	0.87^{a}	0.83^{a}	0.06^{b}	0.153
Medial	Short	-0.03^{x}	0.084	-0.13	-0.10	-0.08	0.19	0.167
	Mid	0.03^{xy}	0.105	-0.34^{a}	-0.13^{a}	0.17^{a}	0.42^{b}	0.208
	Long	0.30^{y}	0.084	-0.11^{a}	0.024^{a}	0.53^{b}	0.78^{b}	0.166
Distal	Short	0.00	0.022	0.00	0.00	0.00	0.00	0.043
	Mid	0.08	0.031	0.30	0.00	0.00	0.00	0.061
	Long	0.02	0.022	0.07	0.00	0.00	0.03	0.043
Side								
Back	Short	0.03	0.047	0.10	0.17	0.01	-0.17	0.093
	Mid	-0.12	0.055	0.00	0.02	-0.21	-0.29	0.109
	Long	-0.06	0.047	0.10^{a}	0.04^{a}	-0.10^{a}	-0.29^{b}	0.093
Hip	Short	0.05	0.055	0.05	-0.04	-0.13	0.29	0.108
Bone	Mid	-0.06	0.062	0.07	-0.12	-0.29	0.08	0.124
	Long	-0.14	0.054	0.02^{a}	-0.16^{a}	-0.38^{b}	-0.06^{a}	0.108
Shoulder	Short	0.02	0.014	0.00	0.00	0.07	0.00	0.027
	Mid	0.00	0.020	0.00	0.00	0.00	0.00	0.040
	Long	0.01	0.014	0.00	0.03	0.00	0.01	0.027
Flank	Short	-0.02	0.055	-0.06	0.01	0.15	-0.17	0.108
	Mid	0.00	0.063	-0.16	0.05	0.25	-0.17	0.124
	Long	0.03	0.054	-0.06	0.05	0.25	-0.14	0.108
Sacrum	Short	-0.02	0.056	-0.02	-0.02	0.10	-0.15	0.112
	Mid	-0.09	0.048	-0.02	-0.02	-0.08	-0.25	0.959
	Long	-0.07	0.046	0.01	-0.05	-0.07	-0.18	0.092
Pin Bone	Short	-0.03	0.051	-0.07	-0.12	0.15	-0.08	0.101
	Mid	-0.12	0.059	-0.10	-0.17	-0.04	-0.17	0.118

	Long	-0.13	0.060	-0.10	-0.17	-0.01	-0.24	0.120
Back legs								
Lateral	Short	0.18^{x}	0.103	0.22	0.24	0.15	0.11	0.205
Tarsal	Mid	0.53^{y}	0.111	0.55	0.78	0.54	0.25	0.221
	Long	0.39^{xy}	0.103	0.50	0.45	0.42	0.19	0.204
Dorsal	Short	-0.20^{x}	0.118	-0.32	-0.33	-0.06	-0.10	0.233
Calcanei	Mid	-0.01^{xy}	0.132	0.08	-0.22	-0.04	0.17	0.262
	Long	0.08^{y}	0.117	0.03	-0.13	0.40	0.03	0.233
Hind Leg	Short	0.02	0.065	0.02	0.04	0.03	-0.03	0.129
	Mid	-0.08	0.074	-0.05	-0.03	-0.13	-0.13	0.148
	Long	-0.09	0.065	-0.06	-0.02	-0.10	-0.18	0.129
Stifle	Short	-0.08	0.063	0.05	-0.05	-0.10	-0.21	0.125
	Mid	-0.05	0.077	-0.09	0.20	-0.13	-0.17	0.153
	Long	0.05	0.063	0.06	0.14	0.06	-0.04	0.125
Lateral	Short	0.07	0.065	0.20	-0.05	0.04	0.10	0.130
Calcanei	Mid	0.24	0.084	0.37	0.26	0.25	0.08	0.168
	Long	0.17	0.065	0.17	0.09	0.31	0.10	0.129
Medial	Short	0.01	0.051	0.03	-0.03	0.01	0.01	0.101
Calcanei	Mid	0.00	0.045	0.03	-0.02	-0.04	0.04	0.090
	Long	0.05	0.065	0.10	0.05	0.07	0.00	0.129
Lateral	Short	0.18^{x}	0.103	0.22	0.24	0.15	0.11	0.205
Tarsal	Mid	0.53^{y}	0.111	0.55	0.78	0.54	0.25	0.221
	Long	0.39^{xy}	0.103	0.50	0.45	0.42	0.19	0.204
Medial	Short	-0.01	0.028	0.06	0.00	0.00	-0.08	0.056
Tarsal	Mid	-0.01	0.036	0.01	0.01	0.00	-0.04	0.071
	Long	0.01	0.028	0.07	0.07	0.00	-0.08	0.056
Front legs								
Carpal	Short	0.05	0.090	0.08	0.16	0.10	-0.15	0.178
Joints	Mid	0.26	0.102	0.21	0.35	0.29	0.21	0.203
	Long	0.33	0.090	0.24	0.36	0.50	0.22	0.178

[1]The short-term period represents the average scores of weeks 1-3, the mid-term period represents the scores of week 6 and long-term period represents the average scores of weeks 8-10.

[2]Periods means within a column with different superscript (x, y, z) differ ($P < 0.05$)

[3]Treatments means within a row with different superscript (a, b, c) differ ($P < 0.05$)

[4]Average across treatments

[5]Pooled average

3.4.5 Rising and lying ability and resting behaviours

We found that rising ability did not differ significantly between the various tie-rail treatments and Current Recommendation (Table 3.5). All treatments showed a decrease over time in average backwards movement on knees during rising (-10.8%), contact with tie-rail during rising (-14.3%) and overall abnormal rising (-15.7%; $P \leq 0.05$).

Table 3.5. Rising ability measures for Current Recommendation (control), Common on Farm, Neckline1 and Neckline 2 treatments during the short-, mid- and long-term periods[1]

	Periods[2]			Treatments[3]				
Outcome measures	Term	Lsmean[4]	SE	Control	Common on Farm	Neckline 1	Neckline 2	SE[5]
Backwards movement on knees, %	Short	13.3^{x}	2.10	9.3	17.2	18.1	8.8	4.17
	Mid	4.1^{xy}	2.81	-0.9	13.0	2.8	1.4	5.59
	Long	2.4^{y}	2.37	1.3	6.9	0.5	0.9	4.70
Tie-rail contact, %	Short	21.9^{x}	3.16	26.2	26.3	22.2	13.0	6.27
	Mid	10.8^{xy}	3.88	13.7	14.0	8.3	6.9	7.71
	Long	7.6^{y}	3.40	11.1	7.1	5.3	7.1	6.73
Rising time, sec/event	Short	20.6	5.89	6.0	22.0	34.8	19.6	11.67
	Mid	14.9	7.80	4.9	20.1	10.3	24.3	15.52
	Long	15.4	6.61	5.3	15.6	17.8	23.0	13.12
Attempts of rising, Ave./event/d	Short	1.4	0.11	1.3	1.4	1.9	1.2	0.22
	Mid	1.3	0.12	1.2	1.0	1.7	1.1	0.24
	Long	1.2	0.11	1.2	1.1	1.4	1.1	0.23
Delayed rising, %	Short	6.4	2.55	0.5	9.4	10.7	5.1	5.04
	Mid	6.2	2.81	0.7	10.1	6.9	6.9	5.57
	Long	6.6	2.63	-0.4	7.6	12.8	6.6	5.22
Horse rising, %	Short	0.0	0.00	0.0	0.0	0.0	0.0	0.00
	Mid	0.0	0.00	0.0	0.0	0.0	0.0	0.00
	Long	0.0	0.00	0.0	0.0	0.0	0.0	0.00
Overall abnormal rising, %	Short	40.6^{x}	4.55	35.1	47.3	51.9	28.2	9.02
	Mid	27.3^{xy}	5.20	18.6	32.2	40.3	18.1	10.32
	Long	25.0^{y}	4.76	16.9	22.6	39.5	20.9	9.44

[1]The short-term period represents the average scores of weeks 1-3, the mid-term period represents the scores for week 6 and long-term period represents the average scores of weeks 8-10.

[2]Periods means within a column with different superscript (x, y, z) differ ($P < 0.05$)

[3]Treatments means within a row with different superscript (a, b, c) differ ($P < 0.05$)

[4]Average across treatments

[5]Pooled average

Ability to lie down did not differ significantly between the various tie-rail treatments and Current Recommendation (Table 3.6). All treatments showed a decrease over time in average lying intention time (-5.9 s/event), lying-down time (-1.1 s/event), contact with stall during lying (-32.5%) and slipping during lying (-9.4%; $P \leq 0.05$).

Table 3.6. Measures of the ability to lie down for current recommendation (control), Common on Farm, Neckline1 and Neckline 2 treatments during the short-, mid- and long-term periods[1]

	Periods[2]			Treatments[3]				
Outcome measures	Term	Lsmean[4]	SE	Control	Common on Farm	Neckline 1	Neckline 2	SE[5]
Lying intention time, s/event	Short	21.3^{x}	0.79	19.5	23.5	23.3	19.1	1.57
	Mid	18.1^{xy}	1.08	16.0	21.8	19.1	15.3	2.15
	Long	15.5^{y}	0.91	14.1	18.3	15.9	13.6	1.80
Lying-down time, s/event	Short	7.0^{x}	0.23	6.7	7.3	6.8	7.2	0.46
	Mid	6.5^{xy}	0.27	5.9	6.7	6.8	6.4	0.55
	Long	5.9^{y}	0.22	5.6	6.4	5.8	5.6	0.49
Contact with stall, %	Short	74.8^{x}	3.22	67.0	73.4	79.6	79.2	6.38
	Mid	70.1^{x}	4.15	52.9	74.5	72.2	80.6	8.26
	Long	42.3^{y}	3.58	36.8	45.7	57.96	28.6	7.12
Slipping, %	Short	11.3^{x}	1.98	16.4	9.3	13	6.5	3.92
	Mid	16.0^{x}	2.78	19.2	11.6	12.5	20.8	5.54
	Long	2.2^{y}	2.30	4.3	1.2	1.6	1.9	4.58
Attempts of lying, Ave./event/d	Short	1.0	0.61	1.0	1.0	1.0	1.0	0.01
	Mid	1.0	1.03	0.9	1.0	1.0	1.0	0.02
	Long	1.0	0.78	1.0	1.0	1.0	1.0	0.02
Hind quarter stepping, %	Short	16.7	3.17	12.1	20.6	12	22.2	6.29
	Mid	9.7	3.94	7.6	11.5	8.3	11.1	7.85
	Long	18.4	3.45	11.2	14.3	25.4	22.7	6.85
Dog sitting, %	Short	0	0	0	0	0	0	0
	Mid	0	0	0	0	0	0	0
	Long	0	0	0	0	0	0	0
Lying on the right, %	Short	50.2	1.79	53.9	46.9	52.3	47.7	3.56
	Mid	49.9	2.64	44.0	58.3	45.8	51.4	5.27
	Long	54.9	2.11	55.9	54.9	51.9	56.9	4.20
Overall abnormal lying, %	Short	25.9	3.51	26.5	29.2	21.8	25.9	6.97
	Mid	24.3	4.58	23.8	23.3	19.4	30.6	9.11
	Long	22.7	3.93	21.6	15.9	28.8	24.5	7.81

[1]The short-term period represents the average scores of weeks 1-3, the mid-term period represents the scores for week 6 and long-term period represents the average scores of weeks 8-10.

[2]Periods means within a column with different superscript (x, y, z) differ ($P < 0.05$)

[3]Treatments means within a row with different superscript (a, b, c) differ ($P < 0.05$)

[4]Average across treatments

[5]Pooled average

Resting behaviours, such as lying time, number of lying bouts and lying bout duration, did not differ significantly between the various tie-rail treatments and Current Recommendation or over time (Table 3.7).

Table 3.7. Resting behaviour measures for Current Recommendation (control), Common on Farm, Neckline1 and Neckline 2 treatments during the short-, mid- and long-term periods[1]

	Periods[2]			Treatments[3]				
Outcome measures	Term	Lsmean[4]	SE	Control	Common on Farm	Neckline 1	Neckline 2	SE[5]
Total lying time, h/d	Short	11.3	0.24	11.1	11.2	11.3	11.4	0.48
	Mid	11.7	0.27	10.7	11.8	11.9	12.6	0.53
	Long	11.9	0.24	11.5	12.0	12.0	12.0	0.47
No of lying bouts, #/d	Short	13.2	0.46	12.4	13.7	13.8	13.0	0.91
	Mid	13.9	0.50	12.9	14.2	15.5	12.8	1.00
	Long	13.0	0.46	12.1	13.5	14.2	12.4	0.91
Lying bout duration, min/bout/d	Short	56.9	2.62	67.3	51.9	52.9	55.5	5.21
	Mid	63.2	9.26	54.1	52.7	51.4	94.6	18.52
	Long	62.7	3.85	64.0	58.6	55.5	72.6	7.69

[1]The short-term period represents the average scores of weeks 1-3, the mid-term period represents the scores for week 6 and long-term period represents the average scores of weeks 8-10.

[2]Periods means within a column with different superscript (x, y, z) differ ($P < 0.05$)

[3]Treatments means within a row with different superscript (a, b, c) differ ($P < 0.05$)

[4]Average across treatments

[5]Pooled average

3.4.6 Cow and bedding cleanliness and bedding quantity

The percentage of clean flanks, legs and udders was not significantly different between the various tie-rail treatments to Current Recommendation. Additionally, flank, leg and udder cleanliness did not significantly differ over time (Table 3.8).

Bedding cleanliness was not significantly affected by tie-rail treatments and did not significantly change over time (Table 3.8).

The percentage of stalls with bedding deeper than 2 cm during the mid-term period was lower for Common on Farm and Neckline2 compared to Current Recommendation, which contained 33.3% and 25.0% more stalls with deep bedding respectively (Table 3.8). During the long-term period Common on Farm, Neckline1 and Neckline2 had less stalls with deep bedding compared to Current Recommendation, which contained 14.7%, 20.8% and 20.8% more stalls with deep bedding respectively. Current Recommendation only contained 4 stalls out of 12 with deep bedding during the mid-term period and on average only 2 stalls out of 12 with deep bedding during the long-term period. Overall percentage of stalls with bedding deeper than 2 cm across tie-rail treatments did not significantly differ over time.

Table 3.8. Cow and bedding cleanliness and bedding quality measures for Current Recommendation (control), Common on Farm, Neckline1 and Neckline 2 treatments during the short-, mid- and long-term periods[1]

	Periods[2]			Treatments[3]				
Outcome measures	Term	Lsmean[4]	SE	Control	Common on Farm	Neckline 1	Neckline 2	SE[5]
Bedding quantity, % bedding ≥ 2 cm	Short	8.6	0.02	9.4	5.6	11.1	8.3	3.15
	Mid	14.6	0.03	33.3^{a}	0.0^{b}	16.7^{a}	8.3^{b}	6.55
	Long	6.7	0.02	20.8^{a}	6.1^{b}	0.0^{b}	0.0^{b}	3.15
Flank cleanliness, % clean	Short	393.6	0.04	97.2	80.0	100.0	97.2	7.51
	Mid	97.9	0.05	91.7	100.0	100.0	100.0	9.19
	Long	95.6	0.04	94.4	93.3	100.0	94.4	7.51
Leg cleanliness, % clean	Short	96.0	2.29	97.2	86.7	100.0	100.0	4.58
	Mid	100.0	3.69	100.0	100.0	100.0	100.0	7.38
	Long	97.9	2.29	100.0	100.0	100.0	91.7	4.58
Udder cleanliness, % clean	Short	92.9	3.59	91.7	80.0	100.0	100.0	7.19
	Mid	95.8	5.26	91.7	91.7	100.0	100.0	10.52
	Long	91.3	3.59	91.7	84.4	100.0	88.9	71.88
Bedding cleanliness, % clean	Short	80.8	3.72	77.8	84.4	83.3	77.8	7.43
	Mid	82.9	6.08	66.7	90.0	91.7	83.3	12.17
	Long	78.7	3.72	81.9	77.2	83.3	72.2	7.43

[1]The short-term period represents the average scores of weeks 1-3, the mid-term period represents the scores for week 6 and long-term period represents the average scores of weeks 8-10.

[2]Periods means within a column with different superscript (x, y, z) differ ($P < 0.05$)

[3]Treatments means within a row with different superscript (a, b, c) differ ($P < 0.05$)

[4]Average across treatments

[5]Pooled average

3.4.7 *Lameness, BCS, and feeding/rumination time*

Stall lameness scores did not differ significantly between tie-rail treatments compared to Current Recommendation or over time (Table 6). The prevalence of lameness for Current Recommendation, Common on Farm, Neckline1 and Neckline2 was 63.6%, 10%, 50% and 41.7%, respectively, for week 0 and 72.7%, 50%, 58.3% and 41.7% for week 10. The prevalence of lameness behaviours observed in lame cows was: 98.6% uneven, 96.0% rest, 11.2% edge and 2.2% shift.

BCS did not differ significantly between the various tie-rail treatments and Current Recommendation or over time (Table 3.9).

Feeding/rumination time did not differ significantly between the various tie-rail treatments and Current Recommendation or over time (Table 3.9).

Table 3.9. Lameness (score difference from week 0), BCS and feeding/rumination time (% of time/h) for Current Recommendation (control), Common on farm, Neckline1 and Neckline2 treatments during the short-, mid- and long-term periods[1]

	Periods[2]			Treatments[3]				
Outcome measures	Term	Lsmean[4]	SE	Control	Common on Farm	Neckline 1	Neckline 2	SE[5]
Lameness, score diff. from week 0	Short	0.01	0.036	0.06	-0.02	0.00	-0.01	0.072
	Mid	0.03	0.043	0.10	-0.10	0.10	0.01	0.085
	Long	0.03	0.037	0.06	-0.01	-0.02	0.07	0.073
BCS, score	Short	2.5	0.04	2.6	2.6	2.5	2.4	0.07
	Mid	2.6	0.04	2.6	2.6	2.6	2.5	0.07
	Long	2.5	0.04	2.6	2.5	2.6	2.5	0.07
Feeding/ rumination time, % of time/h	Short	53.3	1.56	55.5	50.8	51.8	55.3	3.08
	Mid	53.3	1.62	56.2	51.5	50.7	54.8	3.19
	Long	49.2	1.56	51.5	50	45.8	49.6	3.07

[1]The short-term period represents the average scores of weeks 1-3, the mid-term period represents the scores for week 6 and long-term period represents the average scores of weeks 8-10.

[2]Periods means within a column with different superscript (x, y, z) differ ($P < 0.05$)

[3]Treatments means within a row with different superscript (a, b, c) differ ($P < 0.05$)

[4]Average across treatments

[5]Pooled average

3.4.8 *Production*

We found that production measures did not significantly differ between the various tie-rail treatments and Current Recommendation (Table 3.10). Across all tie-rail treatments some production measures did significantly differ over time.

Table 3.10. Milk measures for Current Recommendation (control), Common on Farm, Neckline1 and Neckline 2 treatments during the short-, mid- and long-term periods[1]

Outcome measures	Periods[2]			Treatments[3]				
	Term	Lsmean[4]	SE	Control	Common on Farm	Neckline 1	Neckline 2	SE[5]
Milk Yield, l/d	Short	41.3^{x}	0.93	41.8	40.5	41.8	41.2	1.84
	Mid	39.6^{xy}	0.95	40.4	38.3	40.5	39.1	1.88
	Long	38.4^{y}	0.93	38.4	37.3	40.0	37.7	1.83
Fat, kg/d	Short	1.6^{x}	0.04	1.7	1.6	1.6	1.6	0.08
	Mid	1.6^{xy}	0.05	1.6	1.6	1.6	1.5	0.09
	Long	1.5^{y}	0.04	1.6	1.5	1.5	1.4	0.08
Protein, kg/d	Short	1.3	0.03	1.3	1.3	1.3	1.3	0.05
	Mid	1.3	0.03	1.3	1.3	1.3	1.3	0.05
	Long	1.3	0.03	1.3	1.3	1.3	1.3	0.05
Lactose, kg/d	Short	1.9^{x}	0.05	2.0	1.9	1.9	1.9	0.09
	Mid	1.8^{xy}	0.05	1.9	1.8	1.9	1.8	0.09
	Long	1.8^{y}	0.05	1.8	1.7	1.8	1.7	0.09
Total Solids, kg/d	Short	5.3	0.11	5.4	5.2	5.3	5.2	0.21
	Mid	5.1	0.11	5.2	5.1	5.2	5.0	0.22
	Long	5.0	0.11	4.9	5.0	5.1	4.8	0.21
SCC, 000/ml	Short	166.1	79.85	360.5	118.6	33.4	151.9	158.37
	Mid	201.0	95.83	376.6	306.8	54.0	66.7	190.53
	Long	176.9	80.05	408.1	140.7	93.7	64.9	158.79
Urea, mg/dl	Short	12.5^{x}	0.33	12.8	12.4	12.1	12.8	0.66
	Mid	12.9^{xy}	0.40	13.4	13.1	12.3	12.8	0.79
	Long	13.8^{y}	0.33	13.9	14.3	12.9	14.0	0.66
BHB, mmol/l	Short	0.1	0.00	0.1	0.1	0.1	0.1	0.01
	Mid	0.1	0.00	0.1	0.1	0.1	0.1	0.01
	Long	0.1	0.00	0.1	0.1	0.1	0.1	0.01
DeNovo fatty acids, %	Short	1.2^{x}	0.04	1.2	1.2	1.1	1.1	0.08
	Mid	1.3^{xy}	0.05	1.3	1.4	1.2	1.2	0.10
	Long	1.3^{y}	0.04	1.4	1.3	1.2	1.2	0.08

[1]The short-term period represents the average scores of weeks 1-3, the mid-term period represents the scores for week 6 and long-term period represents the average scores of weeks 8-10.

[2]Periods means within a column with different superscript (x, y, z) differ ($P < 0.05$)

[3]Treatments means within a row with different superscript (a, b, c) differ ($P < 0.05$)

[4]Average across treatments

[5]Pooled average

3.5 Discussion

In this study we found that different tie-rail positions had an effect on injuries, specifically neck injuries. Whereas, different tie-rail positions did not have an effect on rising and lying ability, resting behaviour, lameness, BCS, feeding/rumination time, cow and stall cleanliness, bedding quantity, and production measures.

3.5.1 *Neck injuries*

Our results show that the position of neck injuries differs according to the tie-rail position. When the tie-rail is high, such as in the Current Recommendation and Common on Farm treatments, injuries appear on the proximal neck (higher portion, closest to the body) of cows. When the tie-rail is lower, such as in the Neckline2 treatment, injuries appear on the medial neck (lower portion, closest to the head) of cows. For tie-rails positioned at an intermediate height and closer to the cow, such as in the Neckline1 treatment, there was an increase in injuries on both the proximal and medial areas of the cows' neck. These results are similar to a study conducted on Canadian tie-stall dairy farms by Zurbrigg et al. (2005), which found that low (71 to 96 cm) and high (116 to 132 cm) tie-rail heights had 70% fewer neck lesions than the midrange (99 to 114 cm) tie-rail heights. However, it is important to note that according to Zurbrigg et al. (2005), the Neckline2 treatment was also in the midrange tie-rail height category. The fact that in the Neckline2 treatment the tie-rail was positioned lower and further away from the cow may have aided the cows in avoiding proximal neck injuries. Bouffard et al. (2017) found that if the tie-rail forward position met or exceeded current recommendation there was a reduced risk (odds ratio: 0.582) of neck lesions and when the tie-rail height met or exceeded current recommendation there was an increased risk (odds ratio: 1.219) of neck lesions. However, we found that regardless of tie-rail height and forward position, all tie-rail placements resulted in an increase in neck injuries, emerging from the cows putting pressure on their neck through repeated contact with the tie-rail (e.g., leaning on the bar during feeding, contacts during transition from lying to standing positions). This result leads to two main issues: the metal bar used as the tie-rail and the tie-rail forward position (35.6 cm). Alternatives to metal tie-rail bars may alleviate pressure on the neck when the cow comes into contact with tie-rail. Therefore, further investigation should be done into alternatives to metal tie-rail bars that are already on the market, such as a chains or flexible bars. A tie-rail forward position exceeding 35.6 cm could also be investigated. However, this may not be as applicable on standard tie stall farms as there is often limited space in front of the stall, sometimes due to the proximity of the front of the stall to the wall.

3.5.2 *Side injuries*

Back injuries improved over time for Neckline2 treatment, and hip bone injuries improved overtime for Neckline1 treatment compared to Current Recommendation treatment. However, both these improvements are a result of the cows starting with different injury levels at the beginning of the trial (e.g., cows in the two treatments showed more improvement overtime because they started with a higher prevalence of injuries in those locations, thus there was more room for improvement). This suggests that tie-rail placement did not have a meaningful effect on hip bone or back injuries. In our study we found that the prevalence of back and hip bone injuries was high (at week 10, the prevalence of back and hip bone injuries across tie-rail treatments were 9.2% and 26.7%, respectively). Brenninkmeyer et al. (2016) also found that hip bone injuries were prevalent (median prevalence: hairless areas = 13%; scabs and wounds = 4%) on farms, concluding that future research should include hip bone injury scoring. Further research should be conducted to determine risk factors for back and hip bone injuries.

3.5.3 Back leg injuries

Our study found that tie-rail placement did not have a significant effect on back leg injuries. However, we did find an increase in lateral calcanei (point of the hock) and hock injuries over time for all cows. Previous studies have found that tie-rail position can be linked to back leg injuries such as hock injuries. For instance, a study conducted on tie-stall farms in Ontario and Quebec by Nash et al. (2016) found that the probability of hock injury was greater the further forward the tie-rail was positioned (Coefficient: 0.0036 ± 0.0066; P-value: 0.003 per cm increase). Softness of the stall base surface and bedding is likely to have an impact on back leg injuries due to repeated contacts with the stall surface (Wechsler et al., 2000; Nash et al., 2016). Older mats may become less abrasive over time and farmers can compensate for abrasiveness by adding more bedding, which can lead to a decrease in the odds of hock injury (Potterton et al., 2011; Nash et al., 2016).

Thus, the general increase in lateral calcanei and hock injuries overtime is most likely due to the installation of new mats at the start of the experiment. The new mats were more abrasive then the old mats, thus requiring an adjustment in bedding management. The decrease in hock injuries in the long term may be due to the barn staff increasing the amount of bedding added in the last weeks of start 2.

3.5.4 Front leg injuries

No variation in front leg injuries between treatments or over time were found in our study. However, almost all cows started with carpal joint injuries. An on farm study performed in Quebec and Ontario suggested that the closer the tie-rail was to the manger wall the greater (odds ratio: 0.834) the probability of knee injuries (Bouffard et al., 2017). Our tie-rail placements were never closer than 17.8 cm (7 inches) from the manger wall; however, this distance may not be sufficient in combination with very little bedding to heal front leg injuries over the 10 weeks of the trial.

3.5.5 *Lying and rising ability and resting behaviours*

We found that the tie-rail placements tested did not have a significant effect on the rising and lying ability of tie-stall housed dairy cows. However, overall abnormal rising and lying behaviours decreased over time starting during the mid-term or the long-term period depending on the behaviour. This suggests that the cows were able to adapt to their new housing environments to a certain extent over time, which is consistent with a previous study looking at the introduction of heifers to tie-stall housing (Jensen, 1999). During the long-term period, rising (15.4 s) and lying down (5.9 s) movement times were longer for rising, but shorter for lying down than what has previously been reported in tie-stall housed cows (2.23 s and 8.5 s respectively; Chaplin and Munksgaard (2001)). It is likely that other aspects, such as little bedding or presence of front leg injuries, may have played a role in the longer rising time observed, independently of the treatment. Cow contact with the stall (the divider and/or the tie-rail) decreased over time during rising and lying down movements, however cows still came into contact with the confines of the stall 42.3% of the time while lying and 7.6% of the time while rising during the long-term period. In general, although the cows adjusted to their new housing environments and showed improvement in lying and rising ability over time, abnormal behaviours such as contact with different elements of the stall during lying and rising events were not eliminated and still prevalent over time. Thus, further research into alternative stall design (e.g., more space, different material, etc.) associated with a quantification of the number of contacts with the confines of the stall would be essential in improving cow experience when changing positions in her housing environment.

The tie-rail placements that we tested did not influence the resting behaviour of the cows. Measures of resting behaviour such as lying time, lying bout duration and number of lying bouts are commonly used as indicators of the cow's comfort in her stall (Haley et al., 2000). The study by Bouffard et al. (2017) suggested that farms where the tie-rail height was at or above current recommendation had a reduced daily lying time and fewer lying bouts, whereas farms with a tie-rail forward position at or longer than current recommendation had an increase in daily lying time. In contrast, our results are similar to Haley et al. (2001) who found that even if the lunge space (i.e., space available in front of the stall) is restricted, measures of resting behaviours such as lying time and number of lying bouts are not affected and other aspects such as stall base softness/comfort have a greater impact on resting behaviour. Overall, in this study the average daily lying time was within the range reported in previous studies in tie-stall cows (Rushen et al., 2007; Tucker et al., 2009; Charlton et al., 2016).

3.5.6 *Cow and stall cleanliness and bedding quantity*

Tie-rail placement did not have an effect on stall or cow cleanliness. This is in contrast with Zurbrigg et al. (2005), which found that increasing tie-rail height increased the prevalence of clean udders on farm. Bouffard et al. (2017) found that in tie-stalls there was an increased risk of dirty udders when the tie-rail placement met or exceeded current recommendation. This finding is similar to what is found in free-stall barns, where neck rails positioned further from the stall curb resulted in a decrease in cow and stall cleanliness (Tucker et al., 2005; Bernardi et al., 2009). During our trial, we scored stall cleanliness at the time when the stalls would have been the dirtiest, which was in the morning before stalls were scraped for the morning milking. The research farm prioritized cleanliness; thus, the barn staff scraped the stalls whenever the stalls contained any faeces or urine (at least 7 times per day) and cows were brushed occasionally. As part of our experimental design, we chose not to change the barn’s cleaning routine. Prioritizing a clean barn is a management strategy commonly found on Quebec dairies as milk quality has been the main focus of the Canadian milk quality (CQM) program since it launched in 2010 (LégisQuébec, 2017). The high frequency of scraping may be the reason we did not find that tie-rail placement had an effect on cow or stall cleanliness. The effect of tie-rail placement in tie-stall barns on cleanliness measures should therefore be further investigated perhaps with a more detailed scoring method similar to that used by Tucker et al. (2005), who observed how many times cows defecate and urinate in their stall.

Overall, we did not find a relevant difference in bedding quantity between tie-rail placements since the bedding quantity was low (less than 2 cm) as per bedding management routine in the research barn across treatments. As explained previously, new mats were installed at the beginning of the project and the barn's bedding management was established as the trial progressed. Although we acknowledge that the quantity of bedding was below recommendation, this is unfortunately representative to what is found on commercial tie-stall farms in Canada (Nash et al., 2016).

3.5.7 *Lameness, BCS and feeding/rumination time*

Tie-rail placement did not have a significant effect on lameness and did not help decrease the initial prevalence of lame cows recorded at the start of the trial (42% of cows lame at week 0). A study conducted on Canadian tie-stall farms found an increased risk of lameness (odds ratio: 1.219) when tie-rail height met or exceeded the current recommendation and a reduced risk of lameness (odds ratio: 0.760) when tie-rail forward position met or exceeded the current recommendation (Bouffard et al., 2017). In our study, tie-rail treatments were only applied for a 10-week period; therefore, it is possible that the current study was not long enough to observe an effect of tie-rail placement on lameness. However, a study on free-stall barns performed by Bernardi et al. (2009) found that neck rails closer to the stall curb increased lameness (gait scores) after only 5 weeks. It is possible that other aspects of the stall (e.g., stall base softness), management practices (e.g., hoof trimming strategy) or cow status (e.g., body injuries) contribute more to the lameness of tie-stall housed dairy cows (Cook, 2003; Brenninkmeyer et al., 2013; Brotzman et al., 2015). Furthermore, the tie-rail placements tested were not positioned at extreme heights or forward positions. For instance, in this study the tie-rail was not positioned higher than 121.9 cm or closer than 17.8 cm from the manger wall for forward position. Additionally, we found that the most common behaviours observed in lame cows were uneven weight bearing when standing (rest) and uneven weight bearing while moving from side to side (uneven), similarly to previous findings (Palacio et al. (2017).

Tie-rail placement did not have an effect on BCS of the cows. The average BCS of the cows in this study was 2.53, which is lower than ideal considering that this experiment used a mix of early, mid- and late lactation cows. The Dairy Cattle Code of Practice states that ideally cows should have BCS between 2.50 to 3.25 in early lactation, 2.75 to 3.25 in mid-lactation and 3.00 to 3.50 in late lactation. However, we expect the BCS of the cows used in our experiment to be good representation of BCS found on commercial farms, since it has been reported that dairy cows have relatively low BCS in Canadian dairies (Vasseur et al., 2015).

The feeding/rumination time of trial cows was not affected by tie-rail placement. Bikker et al. (2014) used the same ear-mounted data loggers and using the same technology found that cows spent on average 42.6% of their time ruminating and 9.9% of their time eating. This is similar to what we found in our study, where the average combination of time cows spent feeding and ruminating (feeding/rumination time) was 51.9%. Total time spent exhibiting feeding/rumination behaviour was analyzed in this study instead of the individual behaviours because the combination has been found to be a more accurate representation of tie-stall cows' daily nutritional activities (Zambelis et al. 2018b).

3.5.8 *Production*

We found that tie-rail placement did not have an effect on milk production quantity or components. There was a change in milk yield and certain milk components over time, which could be a result of changes in cow physiology over the course of her lactation or different environmental factors like temperature or diet that varied across the 20 weeks of trial (Sutton, 1989; Fisher et al., 2008; Bernabucci et al., 2010; Cobanoglu et al., 2017).

3.6 Conclusion

Our results showed that all tie-rail placements tested resulted in neck injuries, with the position of neck injuries simply shifting with the change in tie-rail placement. Cows are clearly coming in contact with the metal tie-rail bar, which puts pressure on the neck, and repeated contact causes rubbing/friction on the neck during lying-down and rising motions. To reduce the pressure on the cows' neck when coming in contact with the tie-rail, alternatives to metal tie-rail bars, such as a flexible bar or chain, should be investigated further. Alternatively, to reduce contact with the metal tie-rail bar one could investigate positioning the tie-rail further from the manger wall/cow. The results of this study also showed that abnormal behaviours during lying and rising movements were frequent, resulting from contacts with different aspects of the confines of the stall such as the dividers. These findings lead to questions regarding whether similar results would be seen in free-stall housing systems. Indeed, many of the results of our study could be associated with aspects of the stall itself, which is a characteristic of both tie-stall and free-stall housing systems. Overall, our results show that dairy cows are limited in their ability to move within their environment without coming in contact with the stall confines (tie-rail and divider bars), warranting further research to determine the benefits of designs and systems that provide fewer obstacles through the elimination of some stall hardware and increased individual space such as larger or longer stalls.

CHAPTER 5. GENERAL DISCUSSION

Few studies have investigated the effect of tie-rail placement on dairy cow welfare. The objective of the literature review was to determine the risk factors identified as poor welfare that are associated with tie-rail placement. Additionally, similar constructs to the tie-rail such as neck-rail and feed-rail placements in free-stall barns have been reviewed to determine their effect on the welfare of dairy cows. We found that there are some conflicting findings between what studies have found to be ideal for proper tie-rail height and forward position. For instance, an epidemiological study by Bouffard et al. (2017) found that when tie-rail height met or exceeded the current recommendation dairy cow welfare was reduced, and when tie-rail forward position met or exceeded the current recommendation welfare was improved. In contrast, Zurbrigg et al. (2005) found that high tie-rail placement improved the welfare (reduced neck injuries) of dairy cows compared to tie-rails with midrange heights and Nash et al. (2016) also found that increasing tie-rail forward position reduced dairy cow welfare (increased risk of hock injury). These conflicting results may reflect that the effects of other stall configurations and management practices, and their interaction with rail placement, could not be isolated and/or differentiated in commercial settings. Additionally, the effect of tie-rail placement on certain outcome measures of welfare such as dairy cow lying-down and rising ability have yet to be tested.

The objective of the study presented in Chapter 3 was to determine the effect different tie-rail height and forward position combinations have on outcome measures of dairy cow welfare, in an attempt to determine an ideal overall tie-rail placement. Since cows are considered to come in contact with the tie-rail often when rising and press upon the tie-rail while they are feeding, we hypothesized that dairy cow welfare would improve when tie-rails were positioned to follow the natural slope of the cow's neck when they are feeding or rising. However, we found that every tie-rail placement tested in this experiment resulted in neck injury; the neck injury location shifted based on tie-rail placement. Neck injuries occurred higher on the cow's neck line (proximal neck) when tie-rail was positioned higher off the ground and neck injuries occurred lower on the cow's neck line (medial neck) when the tie-rail was positioned closer to the ground. One of the new tie-rail placements tested, that followed the cow's neck line (Neckline1), resulted in neck injuries on both the proximal and medial neck. Neckline1 was positioned closer to the cow and at a medium height compared to the other tie-rail placements tested. This is consistent with the findings of Zurbrigg et al. (2005), who found that midrange tie-rail heights resulted in more injuries. Additionally, we found that although lying and rising ability of dairy cows improved overtime abnormal lying and rising events such as contact with stall (divider bars and tie-rail) were still highly prevalent for all cows across tie-rail treatments. This implies that dairy cows are often coming in contact with the confines of their stall (tie-rail and divider bars).

In the future, studies should investigate ways to reduce neck injuries and abnormal lying and rising. For instance, studies could investigate alternatives to the metal tie-rail bars as they may reduce the pressure placed on the cow's neck when they come in contact with the tie-rail. Alternatives that are currently commercially available include a flexible tie-rail bar or a chain. To reduce contact with the tie-rail, future studies should investigate tie-rails that are positioned even further from the cow then what is currently recommended. Another option would be to investigate housing systems with fewer obstacles in individual cow space, through the elimination of stall hardware such as deep bedded packs or compost packs.

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