

**A cow in motion: The impact of housing systems on movement
opportunity of dairy cows and the implications on locomotor
activity, behaviour, and welfare**

BY

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ABSTRACT

Focusing on the impact of housing environments that provide dairy cows with differing levels of movement opportunity, the aims of the studies included in this thesis were to 1) validate the technology that we use to measure locomotor activity within a tie-stall system, 2) determine whether providing tie-stall cows with a deep-bedded loose pen during the dry period increased locomotor activity, improved gait, and benefited lying behaviours, and 3) investigate the differences in locomotor activity and time budget of cows housed in free-stall and strawyard housing systems both in the winter after a restricted period of time indoor and in the summer following a period of free-access to pasture.

It was necessary to start with a test of the validity of IceTag pedometers, used in subsequent studies, to measure locomotor activity in tie-stall cows. The results of this validation study showed a high correlation between video observation of step data and the data recorded by the IceTag pedometers. These pedometers are accurate for measuring step activity in tie-stall-housed dairy cows; however, the definition of a step used in this study included more minor movements of the leg (e.g., foot lift without additional movement, partial steps) than what would traditionally be considered a step in a loose-housing environment (e.g., a full swing of the leg while walking). This should be considered when utilizing this technology for more restrictive housing systems.

The following studies established the impact of housing system on movement opportunity of dairy cows, starting with an investigation of the provision of a deep-bedded loose pen (LP) to tie-stall (TS) dairy cows during an 8-wk dry period. Lying time was numerically higher for cows in LP than in TS (14.4 h/d vs. 13.0 h/d, respectively), possibly as a result of a more compressible, comfortable lying surface. LP cows also exhibited more lying postures, particularly regarding hind leg postures, with more space allowing cows the opportunity to extend their hind legs 20% more than TS cows. Cows in the TS treatment were not only more restricted in space, but stall hardware

also created a reduction in ease of movement when transitioning between standing and lying, with contact with the dividers of her stall occurring five times more often for TS cows than contact made between LP cows and their pen enclosure. This also resulted in significantly higher displays of overall abnormal lying behaviours in TS cows, signifying possible issues regarding ease of movement at the stall.

Interestingly, there was no difference in step activity between LP and TS cows (842 vs. 799 steps/d, respectively), and yet LP cows showed greater improvement in gait over the 8-wk dry period. This is particularly evident in the significant improvement in joint flexion (-0.4 vs. +0.2, LP vs. TS). More compressible flooring in the LP treatment may have offered more comfort to the cow when walking and standing. The step quality in the LP may also have been greater, with more space allowing for fuller movement of the legs compared to steps in TS, where the previous validation study suggested that step results were more likely to include smaller leg movements. The results of the lying behaviours may provide insight into why joint flexion showed more improvement overall, as well, with the more compressible lying surface cushioning the carpal joints when lying down and more space to extend the hind leg while lying providing more relief to tarsal joints.

As the stall itself may have had a considerable impact on the results of the dry cow housing study, the question became: how would a free-stall (FS), which still has a restrictive lying area but more opportunity to move outside of the stall, compare to a strawyard (SY), a deep-bedded and stall-free system? It was found that step activity between the two systems did not differ, with movement opportunity in both housing areas likely limited by the similar amount of surface area provided. SY cows had more lying bouts during the summer season and socialized more in the winter than FS cows, but otherwise showed no differences in overall time budget. However, when

considering the locomotor activity of cows outside of the treatment housing, we find that cows that displayed the highest levels of step activity in the treatment housing were also the ones that visited pasture more often, suggesting that more consideration is warranted in future studies as to the individual differences in locomotor activity expression as a means to find options to more effectively increase movement opportunity. The summation of the information and findings presented in this thesis aim to provide more insight on how housing systems and management practices impact movement opportunity for dairy cows as well as the associated benefits. This can, in turn, lead to better recommendations on the feasible ways – both big and small – that producers can improve cow health and overall well-being through offering the cow something that is intrinsic to her being: the opportunity to move.

RÉSUMÉ

Avec pour visée d'évaluer les impacts des systèmes de logement offrant différents niveaux d'opportunité de mouvement aux vaches laitières, les buts des études incluses dans cette thèse étaient de: 1) valider l'utilisation d'une technologie pour quantifier l'activité locomotrice d'une vache logée en stalle attachée; 2) déterminer si l'activité locomotrice, la motricité et la capacité de repos des vaches taries est améliorée par la provision d'un logement de tarissement en enclos sur litière profonde plutôt qu'une stalle attachée; 3) étudier les différences au niveau de l'activité locomotrice et du budget-temps des vaches logées en stabulation libre ou en système sans logettes, en hiver (suivant une période sans accès à l'extérieur) et en été (suivant une période de libre accès au pâturage)

Il nous fallut d'abord valider l'emploi du podomètre IceTag, utilisé dans les études suivantes, afin de s'assurer qu'il puisse quantifier de façon fiable l'activité locomotrice des vaches en stabulation entravée. Nos données ont montré une forte corrélation entre le nombre de pas mesurés via observation vidéo et les décomptes des IceTags utilisés dans cette étude. Les podomètres semblent donc fiables pour compter les pas effectués par les vaches en stalle attachée; il faut toutefois spécifier que la définition de pas utilisée dans le cadre de cette étude incluait des mouvements (e.g. lever du pied sans mouvement vers l'avant, pas incomplet) souvent exclus des définitions traditionnelles d'un pas (i.e., enjambée complète effectuée par la patte). Ce fait devrait être considéré lors de futures utilisations de cette technologie dans des systèmes de logement plus restrictifs tels que la stabulation entravée.

Les deux études suivantes visaient à évaluer l'impact des systèmes de logement sur les opportunités de mouvement des vaches laitières. La première des deux comparait le logement en enclos sur litière profonde (LP) à la stabulation entravée (TS) durant une période de tarissement de 8 semaines. Le temps de repos était numériquement plus élevé chez les vaches en enclos que

celles en stalle (14,4 vs 13,0 h/j), un résultat probablement dû à la compressibilité et au confort accrus de la surface de couchage des enclos. L'espace plus généreux de l'enclos a également permis à ces vaches d'utiliser plus de postures de repos, notamment d'étendre davantage leurs pattes arrière, ce qu'elles ont fait 20 % plus souvent que les vaches en stalle attachée. Nous avons constaté qu'en plus de la taille, les éléments de structure de la stalle en eux-mêmes diminuaient l'aisance de mouvement des vaches en stalle, en particulier lors des mouvements de lever et de coucher : la fréquence des collisions avec les barres et diviseurs de la stalle était cinq fois plus élevée en stalle qu'en enclos, et la prévalence des mouvements de coucher anormaux était significativement plus élevée chez les vaches logées en stalle.

Il est intéressant de noter que malgré l'absence de différence entre les deux traitements pour ce qui est du nombre de pas (842 vs 799 pas/j en enclos et en stalle, respectivement), la capacité locomotrice des vaches logées en enclos s'est plus améliorée au fil des 8 semaines du tarissement que celle des vaches logées en stalle. Une mesure où cet effet est aisément distinguable est la flexion des articulations (-0.4 vs +0.2, enclos vs stalle). Il est possible que la surface plus compressible de l'enclos ait offert aux vaches plus de confort pour se déplacer ou simplement se tenir debout, ou que l'espace plus grand leur ait permis d'effectuer des pas d'une meilleure qualité qu'en stalle, ce que nous laisse présager les résultats de notre étude de validation des podomètres. L'étude des comportements de repos nous apporte d'autres explications potentielles : en effet, la surface de couchage plus compressible a probablement amorti davantage les chocs au niveau des articulations du carpe lors des mouvements de coucher, alors que l'espace additionnel a contribué à soulager les jarrets en permettant aux vaches d'étirer davantage leurs pattes arrière lors du repos.

Puisque la structure de la stalle elle-même a probablement eu un impact considérable sur les résultats de notre étude sur le logement des vaches tarées, une nouvelle question s'est imposée:

une stabulation libre (FS), dont l'aire de repos comporte plusieurs éléments limitant la liberté de mouvement des vaches, restreint-elle plus les opportunités de mouvement des vaches laitières qu'une étable sans logettes avec litière profonde de paille (SY)? Les données collectées ne montrent aucune différence entre ces deux systèmes du côté du nombre de pas, l'aire totale fournie à chaque vache, similaire dans les deux systèmes, étant probablement le facteur limitant le plus important à cet effet. Les comportements des vaches dans l'un et l'autre des systèmes n'ont pas différé, à l'exception du nombre d'épisodes de repos, plus élevé dans le système sans logettes durant l'été, et des comportements de socialisation, plus fréquents en hiver chez les vaches du système sans logettes que dans la stabulation libre. Cependant, nous avons constaté que le niveau d'activité locomotrice est une composante fortement associée à la vache, les individus ayant les plus grands nombres de pas à l'intérieur étant également ceux qui avaient visité la pâture le plus fréquemment. Nous recommandons donc de considérer plus attentivement les variations entre les individus lors de prochaines études portant sur l'activité locomotrice des vaches laitières, pour plus facilement identifier les options qui amélioreront effectivement les opportunités de mouvement des vaches laitières.

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CONTRIBUTION TO KNOWLEDGE

CHAPTER II

The review chapter of this thesis provides a thorough overview of the existing knowledge from the last half-century of literature that relates to or directly mentions the concept of exercise in dairy cattle. The degree of differences between how each study interpreted the definition of exercise and how this interpretation then impacted the ways in which researchers set out to provide and measure exercise warranted a comprehensive review of the literature and a digestion of the materials in a way that connected all of these existing definitions. The original contribution in this chapter lies in the provision of a new definition for ‘exercise’ that fits all interpretations that are presented in the literature, introducing the idea of ‘movement opportunity’ as a more fitting explanation for what is actually provided in most research studies. The original contribution in this chapter also lies in the inclusive compilation of potential influencing factors on locomotor activity associated with the level of movement opportunity provided to the cow, offering a solid basis on which future research on the topic can be derived.

CHAPTER III

This chapter’s contribution to knowledge is the validation of the IceTag pedometer, a device very commonly used in research of dairy cattle and other animal species, for tie-stall use – an environment for which this type of pedometer was not previously validated. Moreover, we established that the foot on which the pedometer is mounted has no impact on its ability to accurately record step activity. This confirms that the leg on which the pedometer is mounted will not bias the results when used in a tie-stall system. Finally, this study provided an increased understanding of the mechanics of a step in a tie-stall compared to that found in the literature regarding loose-housing, with minor lateral and longitudinal movement unrelated to walking

registering as full steps in more restrictive housing. As we know that cows still exhibit movement within the stalls, regardless of an inability to take full strides, this allows for a better comparison of step and movement activities between tie-stall and loose-housed animals.

CHAPTER IV

Original contributions to knowledge found in Chapter IV relate to the furthering of our understanding of how the cow's housing environment affects not only her lying time, but also less researched aspects related to how she transitions between standing and lying and how she rests when lying. This study presented a new method of measuring rising and lying ability (created in a joint effort between colleagues Athena Zambelis, Jessica St John, and Véronique Boyer, all from Dr. Elsa Vasseur's lab), contributing to our understanding of the effects of space and stall hardware on the cow's ease of movement over the course of the dry period. This study filled in gaps in knowledge regarding how the cow utilizes her given environment when lying to exhibit different postures that may be indicative of her level of comfort and restriction. Lying postures were measured using an ethogram and methodology, also created in partnership with Véronique Boyer. This is the first study, to the author's knowledge, that explores these multifaceted aspects of cow lying behavior in dry cows. As the loose-pens are a representation of existing on-farm housing for dry cows, this study thus helps establish the benefits that this housing contributes to cow comfort and ease of movement, increasing the appeal of further implementation on commercial farms.

CHAPTER V

Chapter V, which presents the gait and locomotor activity aspects related to the same study presented in Chapter IV, increases our general understanding of how the cow's environment can impact her leg health. This study offers insight on the importance of space and flooring for cow joint health and shows that a loose-pen or similar environment can result in improvement of leg

health for dry cows heading into their next lactation. Furthermore, this study provided evidence of increased locomotor activity tending to lead to improvements in cow gait and overall lameness, regardless of housing treatment. This information can compel future studies to consider the individual cow's motivation to perform locomotor activity and that cows provided with the same movement opportunity in their housing systems may not utilize it the same way, potentially diluting the benefits of such housing systems.

CHAPTER VI

As producers look to transition from tie-stall housing to loose-housing systems, there are two primary options that they will consider: a free-stall or a deep-bedded pack. However, there is a lack in knowledge as to how these two systems compare to one another, particularly within controlled experimental environments, necessitating the research conducted in the study presented in Chapter 6. This study established that cows do not present different locomotor activity in the two environments. This study did confirm, though, that lying behaviours are affected by the provision of strawyards, possibly in association with the more comfortable lying surface and greater lying area free of stall hardware to impede on lying ability. We also demonstrated that the same cows will socialize more in the strawyard than in the free-stall. Finally, this study touched on the importance of individual considerations when measuring locomotor activity, with cows that performed higher levels of locomotor activity in both the free-stall and strawyard housing options correlating significantly with the number of visits that those cows took to pasture when not housed in these treatment areas. This furthers the idea presented in Chapter 4 that, while providing greater movement opportunity through housing, indoor systems may not be enough to evoke the level of locomotor activity that some animals want to exhibit and possibly need to exhibit to benefit her health and welfare.

CONTRIBUTION OF AUTHORS

In this thesis, four co-authored manuscripts are presented.

Authors of manuscripts 1, 2 3, and 4 (Chapters III, IV, V, and IV, respectively) are as follows:

Elise Shepley (primary author, manuscripts 1-4), Elsa Vasseur (1-4), Joop Lensink (4), Hélène Leruste (4), Marianne Berthelot (1), Giovanni Obinu (2), and Tanguy Bruneau (2).

Elise Shepley co-conceptualized manuscripts 1 and 4 as well as designed and conducted the research studies which resulted in the finding presented in manuscripts 1-4. She also trained and managed all interns and research assistants that assisted in the data collection and data handling process including the students that co-authored manuscripts 1 (Berthelot) and 2 (Obinu and Bruneau). Additionally, Elise analyzed the data for manuscripts 2-4 and supervised the analysis of the data from manuscript 1 and was the primary author on all four manuscripts.

Elsa Vasseur supervised the primary author, conceptualized the experiments comprising manuscripts 2 and 3, and provided assistance in the formulation of all study designs. Elsa also reviewed and co-authored manuscripts 1-4. Joop Lensink and Hélène Leruste co-conceptualized the study presented in manuscript 4 with the primary author, as well as assisted with the design and execution of the study. Both reviewed and co-authored manuscript 4.

Marianne Berthelot, Giovanni Obinu, and Tanguy Bruneau assisted in data collection and data handling related to the studies presented in manuscript 1 (Berthelot) and 2 (Obinu, Bruneau) as a component of their respective degrees. All three served as co-authors for their respective manuscripts. Marianne also carried out the analysis of data for manuscript 1 under the supervision of the primary author.

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CHAPTER 1 — INTRODUCTION AND THESIS OBJECTIVES

1.1 INTRODUCTION

The modern dairy industry looks quite different now than it did a century prior, trading in pasture-based systems for predominantly indoor housing systems. Intensification is widespread across most areas of agriculture and livestock production due to an increased global demand for products coupled with increasing competition with other economic sectors for land (Garnett et al., 2013). Within the dairy industry, this intensification is characterized by increased indoor confinement and increased production levels. In Canada, this has led to a shift to primarily tie-stall-based housing, with 74 % of cows housed in tie-stalls and 26 % of cows in free-stalls (CDIC, 2018). Intensification in the dairy industry has changed not only the ways in which cows are housed, but also the modern dairy cow herself. The average cow dramatically outperforms her predecessors of a mere half century past with more than double the average annual production (Oltenacu and Broom, 2010) at around 10,519 kg of milk/year in Canada (CDIC, 2018), and 10,500 (USDA, 2019) and 6,859 kg/year (European Parliamentary Research Service, 2018) in the US and European Union, respectively. As a result, the nutritional demand of the cow experienced a corresponding increase with this increase in milk production, requiring a higher input of energy-dense feeds which became more practical to meet though indoor housing (Knaus, 2015).

Intensification within the dairy industry has also changed dairy cow health (Oltenacu and Broom, 2010), behavior (Krohn *et al.*, 1992), and overall fitness and lifespan (Horn *et al.*, 2012), raising welfare concerns. In particular, high yielding cows within these systems are associated with higher incidences of involuntary culling and lower mean ages of cows in the herd, which has a subsequent impact on both the fiscal certitude of the producer (Langford and Stott, 2012) and on environmental sustainability (Bell *et al.*, 2011), not to mention the overall welfare of the animal.

Moreover, members of the public have voiced concerns regarding the restrictive nature of indoor dairy housing (Robbins *et al.*, 2019), stating that the ideal dairy farm should include some form of outdoor access – preferably pasture (Cardoso *et al.*, 2016).

To understand how changes in dairy cow housing systems can affect such a pronounced effect on the cow and on the societal perception of the dairy industry, it is necessary to first determine what distinguishes indoor housing from pasture-based housing (Figure 1.1). Indoor housing systems share the key distinction of restricting cows to the indoors of a barn, however, the level of restriction can be perceived as variable depending on the type of indoor housing. Tie-stall housing, for example, is characteristic not only of indoor confinement, but confinement to a stall as well (Figure 1a). Loose-housing systems release the cow from her stall, but differ in a number of other ways. For instance, free-stalls, still utilize stalls for the cow's lying area and, therefore, carry similar restrictions with regard to activity within the stall, but do not tether her to the stall, allowing for more movement within other areas of the housing system (Figure 1b). Deep-bedded packs can be characterized by more open, combined walking and lying areas that generally contain more compressible flooring, such as those found in strawyards (Figure 1c) and compost-bedded packs (Figure 1d). All of these housing systems, both tie-stall and loose-housing, can be combined with outdoor access (e.g., exercise pasture, exercise yard, paddock) to increase the complexity and size of the allotted housing area (Figure 1e).

Pasture is a sharp contrast to these indoor housing systems, with cows housed outdoors for the duration of the grazing season (Figure 1d). Previous research shows that cows benefit greatly from pasture housing and outdoor access, be it through the facilitation of more normative behavioural expression (Loberg *et al.*, 2004), the reduction of health issues such as lameness



Figure 1.1 Dairy cattle housing systems: tie-stall (a), free-stall (b), strawyard (c), compost pack (d), outdoor exercise yard (e), and production pasture (f)

(Hernandez-Mendo *et al.*, 2007), improvements to comfort when resting (Krohn and Munksfaard, 1993), reduction of injuries (Keil *et al.*, 2006), or the plethora of other benefits attributed in the literature to pasture. While these benefits make pasture sound like a clear housing choice for producers, for a number of reasons (e.g., geographic location, land availability, forage quality, level of income) pasture may not a feasible option for all producers. As such, it is necessary to

determine what aspects of pasture may be most influential on the cow in order to offer alternatives to dairy producers.

One such key feature associated with the benefits of pasture is its perceived connection to exercise in dairy cattle research. In fact, this perceived notion that exercise can be manipulated by alterations to the cow's environment, generally through the addition of more space through outdoor access or pasture, is frequently utilized in the literature, and yet inconsistent in the ways in which said 'exercise' is defined, measured, and provided. This leads to the question of whether or not we are looking at exercise provided to dairy cows in the correct way or if, perhaps, what we are offering dairy cows through their housing environments requires a different definition all together.

From early studies examining a purer form of exercise in dairy cattle (e.g., Anderson *et al.*, 1979; Blake *et al.*, 1982), patterns emerge linking improved physical fitness with locomotor activity. Technology has further enabled us to associate locomotor activity (e.g., steps taken, motion level, distance traveled) with the housing types in which the measures were taken. To equate the level of locomotor activity possible in an indoor loose-housing system to that of a pasture-based system is similar to comparing apples to oranges, and with the quantitative measures provided through technological devices, we can see just how dissimilar (or similar in some cases), different dairy housing systems are from one another. Even if one acknowledges the connection between locomotor activity and housing systems, the factors that dictate the levels of locomotor activity that are expressed by the cow in different housing environments are complex. Characteristics within housing systems, particularly in indoor confinement systems, such as walking surface (e.g., Telezhenko *et al.*, 2005, Franco-Gendron *et al.*, 2016), environmental obstructions (e.g., Fregonesi and Leaver, 2001), and space (e.g., Telezhenko *et al.*, 2012) can contribute or detract from the locomotor abilities and activities in the cow. The addition of outdoor

access increases this complexity even more, with the duration of time spent outdoors and the frequency of outdoor access impacting the benefits of its use (Keil *et al.*, 2006). Motivation of the individual cow to both perform locomotor activities (Müller and Schrader, 2005), such as walking and exploration of her environment, and her preference to utilize the outdoor space provided (Charlton *et al.*, 2011a, 2011b; Shepley *et al.*, 2017a, 2017b) will also impact the efficacy of outdoor access.

1.2. GENERAL AND SPECIFIC OBJECTIVES

The general objectives of this thesis, explored in different ways in Chapters 2-6, are to delve deeper into what is being measured and provided to dairy cows in the existing literature where exercise is a focus and to use this information to develop a more encompassing definition for what it means when we provide ‘exercise’ to a dairy cow. An additional aim throughout the thesis is to offer insight on how aspects of health are influenced by cow locomotor activity as a means to emphasize the importance of this topic in the dairy industry. Later in the thesis, the ideas of this literature review will be put into practice, beginning with an understanding of how we measure locomotor activity in tie-stalls (Chapter 3). This study’s aim is to establish the accuracy of a pedometer to measure step activity in tie-stall dairy cows and whether the foot on which the device is mounted impacts the step data measured. Chapter 4, 5, and 6 present the effects of different housing types on locomotor activity and outcome measures related to lying and other behaviours, as well as lameness and gait. More specifically, Chapter 4 and 5 study objectives were to determine if housing tie-stall dairy cows in deep-bedded loose-pens during the dry period positively impacted cow lying time, lying postures, and rising and lying-down ability, as well as gait and locomotor activity. Chapter 6 objectives were to see what happens when we compare not a tie-stall and loose-housing system to one another, but instead, two different types of loose-

housing systems commonly found on commercial dairy farms. This study aimed to determine if housing cows in a free-stall versus a strawyard impacted locomotor activity and time budget across two different seasons (summer and winter) and whether cows that expressed more step activity in the summer visited pasture more often when free-access was provided.

CHAPTER 2 – DEFINING ‘EXERCISE’ FOR DAIRY COWS

2.1. FORCED MOVEMENT IN COWS

The concept of providing exercise to dairy cattle is not novel and yet, when investigating the ways in which exercise is interpreted, defined, and applied in the current literature, we see substantial differences in what studies consider to be the provision of exercise to dairy cattle and how such exercise is provided (Table 2.1). The basic definition of exercise is stated by Merriam-Webster’s dictionary as “bodily exertion for the sake of developing and maintaining physical fitness” (Merriam-Webster, 2018). Early studies approached exercising dairy cattle in a way that closely embodied this definition, looking to establish associations between the amount of locomotor activity performed and the cow’s level of physical fitness, measured through aspects of her health and physiology. Akin to walking a dog or working a horse, these studies ensure individual exercise through human manipulation of the cow in controlled environments such as a circular run (e.g., Anderson *et al.*, 1979) or on a treadmill (e.g., Davidson and Beede, 2009), establishing a uniform level of locomotor activity applied to all study animals. These studies have considered speed, distance, and parity when accounting for the effect of exercise on the cow, finding that moderate walking speeds of around 3.25 km/h (Blake *et al.*, 1982; Davidson and Beede, 2009), for a minimum distance of 4 km (Davidson and Beede, 2009) up to 8 km/d (Blake *et al.*, 1982) had a significant impact on cow fitness. Moreover, pregnant cows have an even greater response to increased exercise provision (Davidson and Beede, 2009), indicating that this is a period in the cow’s life where increasing the opportunity to move freely may have the most impact. Based on the findings of the cow’s response to forced exercise, it was also determined that age may affect the exercise requirements of the animal to reach a more fit state, with older cows requiring more exercise (Anderson *et al.*, 1979).

Table 2.1. Main housing types, treatment applied as exercise, and the method of provision of the treatment for current literature regarding the topic of exercise in dairy cattle.

Main housing	Treatment	Method of Provision	Reference
Tie-Stall	Forced Walking	Walked at 2.7 km/h for 0.8-6.4 km/d; cows walked 5.4 km/h for 0.4-1.6 km	Blake <i>et al.</i> , 1982, Exp. 1
		Walked at 3.54 km/h for 3.22 km or 9.68 km daily, 5.48 km/h for 3.22 km, or were not walked	Blake <i>et al.</i> , 1982, Exp. 2
		Walked at 4.0 km/h for either 1.6 or 8.0 km	Blake <i>et al.</i> , 1982, Exp. 3
		Walked outdoors for 2-3 km/d over 2-3 h period or received no exercise	Gustafson, 1993
		Walked outdoors for 2-3 km/d over 2-3 h period or received no exercise	Gustafson and Lund-Magnussen, 1995
		Walked at 3 km/h for 1 h/d or 2 h/d, or cows were not walked	Davidson and Beede, 2003
		Walked at 3.25 km/h for 1.25-1.5 h/d, or were not walked	Davidson and Beede, 2009
Free-Stall	Forced Walking	Walked at 3.54 km/h for 3.22 km or 9.66 km, 5.47 km/h for 3.22 km, or were not walked	Anderson <i>et al.</i> , 1979
		Walked at 5 km/h for either 1.6 km or 8.0 km daily, or were not walked	Lamb <i>et al.</i> , 1981
	Forced Walking or Pasture	Walked at 3.25 km/h for 1.5 h/d, 5x/wk; pastured for 1.5 h/d, 5x/wk; or were not walked/pastured, post-calving	Black <i>et al.</i> , 2017a
		Walked at 3.25 km/h for 1.5 h/d, 5x/wk; pastured for 1.5 h/d, 5x/wk; or were not walked/pastured, 60-d dry period	Black <i>et al.</i> , 2017b
	Free-stall	Free-stall housing of different sizes and stocking densities	Telezhenko <i>et al.</i> , 2012
Tie-Stall	Loose-housing, pasture access	Loose-housing with free access to pasture and exercise yard, tie-stall housing with 1 h/d of outdoor access, or tie-stall housing only	Krohn <i>et al.</i> , 1992
		Cows provided 1 h/d in exercise yard, free access to pasture and an exercise yard, or no exercise under different intensities of milking	Krohn and Munksgaard, 1993
		Loose-housing with free access to pasture and exercise yard, tie-stall housing with 1 h/d of outdoor access, or tie-stall housing only; measured under different milking intensities	Krohn, 1994

Main housing	Treatment	Method of Provision	Reference
Tie-Stall and Loose-Housing	Exercise area	Continuously loose-housed, tethered in tie-stall for 1, 3, or 9 d and loose-housed for remained of 30-d period, or continuously tie-stall housed	Veissier <i>et al.</i> , 2008; Exp. 1
		Tie-stall housing with 1 h/d of access to exercise area, loose-housed with not access to exercise area, tie-stall housing only	Veissier <i>et al.</i> , 2008; Exp. 2
Tie-stall	Outdoor access	Tie-stall housing with 1 h/d outdoor exercise area access either 7 d/wk, 2 d/wk, or 1 d/wk or were housed in tie-stall housing only	Loberg <i>et al.</i> , 2004
		Level of outdoor access (duration and frequency)	Keil, 2006
Tie-Stall and Loose-Housing	Pasture and or outdoor paddock	Cows provided daytime access to pasture and or an outdoor exercise paddock, or tie-stall housed only	Popescu <i>et al.</i> , 2013
	Pasture	Tie-stall housing with year-round pasture/exercise yard access, tie-stall housing with summer access to pasture and minimal winter access, or cows loose-housed and provided year-round pasture/exercise yard access	Regula <i>et al.</i> , 2004
Free-stall	Pasture	Pastured for 4-wk during the dry period or receive no pasturing	Hernandez-Mendo <i>et al.</i> , 2007
		Free-stall housing with nighttime pasturing, or free-stall housing only	Chapinal <i>et al.</i> , 2010
		Pasture-housing or free-stall housing, 60-d dry period	Black and Krawczel, 2016
Free-Stall, outdoor exercise lot	Pasture	Cows housed in either a free-stall with access to an outdoor exercise lot (control) or production pasture	Dohme-Meier <i>et al.</i> , 2014
Assorted	Pasture	Pasturing and duration of time on pasture (0 h; 120-360 h; 420-570 h; 720-1080h)	Burow <i>et al.</i> , 2011
Tie-stall or Free-stall	Exercise yard or Pasture	Tie-stall with access to exercise yard/pasture, tie-stall only, free-stall with access to exercise yard/pasture	Bielfeldt <i>et al.</i> , 2005
Loose-Housing	Exercise yard or Pasture	Type of outdoor access (exercise yard vs. pasture) and amount of time spent outdoors	Jørgensen <i>et al.</i> , 2015
Free-stall	Exercise yard or Pasture	Type of outdoor access (exercise yard vs. pasture) and amount of time spent outdoors	Kismul <i>et al.</i> , 2018

These studies on forced movement of cows form a baseline understanding for the immediate physiological effects of exercise on cows and, to a more limited extent, the long-term benefits to cow herself. However, when looking more extensively at the bulk of research from the previous two decades, we find that the ways in which exercise is applied and studied in most modern studies strays from this more traditional definition of exercise presented by Merriam-Webster's dictionary. They instead investigate the use of less restrictive housing systems, most often in the form of pasture access, as a means to apply 'exercise' in dairy cattle. As such, the benefits of exercise through the unconventional means of forced movement are not easily extrapolated to on-farm dairy practices nor easily comparable to studies looking at exercise as a reflection of the cow's housing. What can be ascertained from these earlier studies is the idea that the 'bodily exertion' resulting in the attainment of improved fitness is associated with a key factor: the level of locomotor activity exhibited by the cow.

2.2. QUANTITATIVE MEASURES OF LOCOMOTOR ACTIVITY USING TECHNOLOGY

Whereas forced movement studies of exercise in cows required extensive human manipulation to quantify the level of physical activity being applied to each cow, technology is making accurate, quantitative assessments of locomotor activity easier, more automated, and more accessible to both researchers and producers. There are three common technological approaches measuring locomotor activity in cattle under different housing systems: Pedometers, global positioning systems (GPS), and video recordings (Table 2.2). The use of technology to provide such quantitative measures, however, is not often used in relation to exercise, although it could prove to be a useful tool in determining the amount of exercise, at both the herd and individual level, possible in different housing environments.

Table 2.2. Methods of measurements of locomotor activity using three different technologies (pedometer, video data, and global positioning satellite (GPS)) for different housing types and lactation stages.

Technology/ Measure	Type	Main Housing	Treatment	Breed	Results	P-Value	Reference
Pedometer							
Step Activity							
Step/d	IceTag	Free-stall, pasture access	Production Pasture	Holstein	4064	P < 0.001	Dohme-Meier <i>et al.</i> 2014
			Free-stall, outdoor exercise lot access		1506		
	IceTag	Free-stall, pasture access	Free-stall, access to pasture	Holstein	1989	—	Eckelkamp <i>et al.</i> , 2014
			Compost pack		1485		
	IceTag	Free-stall	FS, Overall	Holstein ¹	1835	Treatment, P < 0.001 Period, P < 0.01	Black and Krawczel, 2016
			Pasture, Overall		2715		
			Far-off dry		2416		
			Close-up dry		1943		
			Calving		2889		
			Postpartum		1852		
	IceTag	Tie-Stall	Deep-bedded loose-pen, 16.4 m2	Holstein ¹	818	NS	Shepley <i>et al.</i> , 2019b
			Tie-Stall		748		
	IceQube	Free-stall	Overall	Holstein- Friesian	1520	— P < 0.05, Lactation 1 vs 2, 2 vs 3 P < 0.01	Brzozowska <i>et al.</i> , 2014
			Lactation 1		1525		
			Lactation 2		1495		
			Lactation 3+		1541		
			0-10 DIM		1720		
			11-30 DIM		1525		
			31-50 DIM		1451		
			51-70 DIM		1466		
			71-100 DIM		1466		
			101-150 DIM		1480		
			151-250 DIM		1525		
			250+ DIM		1510		
	IceQube	Free-stall, pasture access	Strawyard	Holstein	1045	NS	Shepley <i>et al.</i> , 2018
			Free-stall		1121		

Technology/ Measure	Type	Main Housing	Treatment	Breed	Results	P-Value	Reference
Pedometer							
Step Activity							
Steps/d	IceQube	Sawdust bedded pack, 3.64 ha pasture access	Overall Days before calving; 14 13 12 11 10 9 8 7 6 5 4 3 2 1	Holstein	2374 2122 2209 2262 2309 2215 2130 2235 2421 2557 2454 2542 2490 2585 2708	— NS	Borchers <i>et al.</i> 2017
	Unspeci fied pedome ter	Free-stall	Concrete slatted floor rubberized floor	Brown Swiss	4226 5611	P < 0.01	Platz <i>et al.</i> , 2008
Walking, min/d	IceTag	Free-stall, pasture access	Production Pasture Free-stall, outdoor exercise lot access	Holstein	311 133	P < 0.001	Dohme- Meier <i>et al.</i> 2014
Steps/min when walking	IceTag	Free-stall	Overall 3-9 DIM 28-34 DIM 200-206 DIM	Holstein	27.0 26.9 26.7 27.3	— P < 0.05, early and late	Maselyne <i>et al.</i> , 2017
Motion Index							
Unit/min when walking	IceTag	Free-stall,	Overall 3-9 DIM 28-34 DIM 200-206 DIM	Holstein	78.5 78.4 74.4 82.6	— P < 0.05, early and late	Maselyne <i>et al.</i> , 2017
Unit/d	IceTag	Free-stall, pasture access	Production Pasture Free-stall, outdoor exercise lot access	Holstein	11.8 2.7	P < 0.001	Dohme- Meier <i>et al.</i> 2014
Distance							
Km/d	Suprex	Pasture	Pasture, 20-ha Pasture, 4-ha	Hereford	5.2 3.6	P < 0.05	Anderson & Kothmann, 1977

Technology/ Measure	Type	Main Housing	Treatment	Breed	Results	P-Value	Reference
Video							
Step Activity							
Steps/h	Video	Free-stall	Hard surface Soft surface	Holstein- Friesian	80-90 110-125	—	Jungbluth <i>et al.</i> , 2003
Step/min, all legs	Video	Free-stall	Stall surface; smooth concrete	Holstein- Friesian	4.5	NS	Rajapaksha <i>et al.</i> , 2015
			Stall surface; rough concrete, all legs		4.6		
			Stall surface; rough concrete, 1 hind leg		5.1		
Step/min, back legs	Video	Free-stall	Stall surface; smooth concrete	Holstein- Friesian	3.7	P < 0.01	Rajapaksha <i>et al.</i> , 2015
			Stall surface; rough concrete, all legs		3		
			Stall surface; rough concrete, 1 hind leg		2.9		
Movemen t, %	Video	Free-stall	Large pen (120m2), small group	Holstein	21.2	Pen size, P = 0.016;	Telezhenko <i>et al.</i> 2012
			Large pen (120m2), large group		21.4	Group size, NS;	
			Small pen (60m2), small group		18.9	Density, P = 0.006; %	
			Small pen (60m2), large group		19.6		
Distance							
m/d	Video	Free-stall	Large pen (120m2), small group	Holstein	330.5	Pen size, P = 0.004;	Telezhenko <i>et al.</i> 2012
			Large pen (120m2), large group		330.5	Group size, NS;	
			Small pen (60m2), small group		278.0	Density, P = 0.011	
			Small pen (60m2), large group		262.3		
Other							
Muscle activity, μV	Video	Free-stall	Stall surface; smooth concrete	Holstein- Friesian	126.4	P < 0.01	Rajapaksha <i>et al.</i> , 2015
			Stall surface; rough concrete, all legs		123.6		
			Stall surface; rough concrete, 1 hind leg		143.1		

Technology/ Measure	Type	Main Housing	Treatment	Breed	Results	P-Value	Reference
GPS							
Distance							
Walking, h/d	GPS, Lotek 2200 Series collar	Pasture	Large pasture (76 or 135 ha) Small pasture (28 ha)	Simmford cross ²	0.6; range: 0.2-1.1 0.4; range: 0.3-0.5	NS	Henkin <i>et al.</i> , 2007
Total locomotion , km/d	GPS, Lotek 2200 Series collar	Pasture	Large pasture (76 or 135 ha) Small pasture (28 ha)	Simmford cross ²	2.9; range: 2.5-3.6 2.5; range: 1.7-3.4	NS	Henkin <i>et al.</i> , 2007
Locomotor while grazing, km/d	GPS, Lotek 2200 Series collar	Pasture	Large pasture (76 or 135 ha) Small pasture (28 ha)	Simmford cross ²	1.9; range: 1.6-2.3 1.6; range: 1.0-2.7	NS	Henkin <i>et al.</i> , 2007
Km/d	GPS Hawk	Pasture, 2.02 ha paddock	N/A	Zebu	4.1; range: 3.2-5.3	—	Schlecht <i>et al.</i> , 2003
	GPS Hawk	Pasture, 1.6-1.8 ha paddock	N/A	Beef, Angus- cross ²	3.5; range: 2.9-3.7	—	Liu <i>et al.</i> , 2015

¹ Denotes dry cows

² Denotes beef breeds

For example, GPS is primarily applied for pasture-housed animals, most popularly implemented with beef cows, yielding locomotor distances of 1.6 km to 5.3 km (Henkin *et al.*, 2007, Brosh *et al.*, 2010, Schlecht *et al.*, 2003, Liu *et al.*, 2015), with a majority of locomotor activity (~66 %) linked to grazing activity. As grazing is a key behavior for dairy breeds as well, results for walking distances for dairy cows would be expected to be proportional for the pasture systems presented. While some models of pedometers and associated algorithms allow for the prediction of distance traveled (e.g., 3.6 km/d in 4-ha pasture, 5.2 km/d in 20-ha pasture; Anderson

and Kothmann, 1977), differences in breed, age, size, health status, and even between individual cows may influence stride length and, thus, the accuracy of these values.

For indoor environments, some studies have taken video recording of cows to estimate locomotor activity. While lacking in automation and possibly in precision, video monitoring of locomotor activity requires as little as an overhead mounted camera. Studies may look at estimates of distance by using pre-established grids within the housing system (e.g., free-stall, Telezhenko *et al.*, 2012) or by recording step behavior at the stall (tie-stall, e.g., Rajapaksha *et al.*, 2015). Video recordings are also popularly used in gait analyses as a way to visually determine walking speeds and number of steps taken to traverse specific distance (Jungbluth *et al.*, 2003), or even in conjunction with kinematic analyses of gait (Flower *et al.*, 2007).

The number of steps taken by the animal is the most frequent measure taken by pedometers. A comparison of the total number of steps taken in different housing systems provides insight on the potential level of locomotor activity that can be expected in these systems. For example, tie-stalls, the system associated with the greatest level of restriction of cow movement, yields lower step activity (748 steps/d; Shepley *et al.*, 2019). This is considerably lower than in free-stall (2,353 steps/d, range 1,120 – 4,918; Platz *et al.*, 2008; Brzozowska *et al.*, 2014; Black and Krawczel, 2016; Shepley *et al.*, 2018), loose-housing that provides outdoor access (1,989 steps/d, free-stall with pasture access, Eckelkamp *et al.*, 2014; 2,374 steps/d, bedded-pack with pasture access, Borchers *et al.*, 2017), and pasture (3,390 steps/d, 2,715 – 4,064; Dohme-Meier *et al.*, 2014; Black and Krawczel, 2016). These quantitative values confirm that systems offering either more incentive to move (e.g., grazing on pasture, layout of free-stall areas) or more space to allow for movement, as will be discussed in Section 2.4., can positively influence the level of locomotor activity performed by the cow.

There are limitations at present to the usefulness and reliability of technological measures that must be taken into consideration when considering the association between their locomotion-related outcome measures and cow housing systems. For instance, while useful in its application on pasture, GPS has been noted to have a fairly low success rate for locating position indoors (Forin-Wiart *et al.*, 2015) and cannot be relied upon fully to follow cow movements in a barn. Newer technology, similar to GPS, triangulate very short radio signals within a more specific environment (e.g., indoor housing, GEA CowView) and have been shown to have improved accuracy for cow location within an indoor barn environment, but are still limited in their predictive capabilities for cow activities such as walking (Tullo *et al.*, 2016). Similarly, de Weerd *et al.* (2015) noted limitations on pastures that were forested with accuracy reduced to 57 % in these areas versus 70 % in an open field. Furthermore, the high energy consumption of current GPS devices has led, until now, to low applicability on a daily basis.

Video data allows for the repeated review of cow locomotor activity and gait, but is limited at present in its automation for the tracking of cows and reliability and sensitivity of the visual observation methods. Pedometers have been validated for use in a number of housing settings (e.g., tie-stalls, Felton *et al.*, 2012, Shepley *et al.*, 2017; loose-housing, Higginson *et al.*, 2010; pasture, Elischer *et al.*, 2013), but consistency of recording methods, data handling protocols, and hardware between studies may differ (Anderson *et al.*, 2013). Moreover, the definition of a ‘step’ in more restrictive environments like tie-stalls may also conflate the actual level of locomotor activity being recorded, with more minor movements, which are more likely to occur in tie-stall housing, registering as steps with pedometers (Shepley *et al.*, 2019). The impact of housing on locomotion will be further discussed in Sections 2.4 and 2.5. The data recording interval for both GPS and pedometer devices can also affect their output. For instance, Davis *et al.* (2011) found that

increasing the sampling interval for movement (e.g., 20 s vs. 5 min v 20 min) decreased the mean km/d registered by the device due to the under-sampling of activity between sampling periods.

2.3. QUALITATIVE CHARACTERIZATION OF LOCOMOTOR ACTIVITY BY HOUSING SYSTEM

Previously in this paper, links were made between a more straightforward definition of exercise and locomotor activity. Locomotor activity was then further connected to housing systems through quantitative measurements, finding that the level of locomotor activity recorded was affected by the system in which the cow resides. From a research standpoint, classifying housing systems based on the level of locomotor activity that cows can be expected to display in each allows for a longer application of the treatment being associated with exercise and, thus, allows for long-term analyses of outcome measures of related health, performance, and welfare. This qualitative method of measuring exercise involves the association of different housing systems, most commonly pasture-based systems, with the level of exercise that they are perceived to provide to the dairy cow. On one end of this spectrum is tie-stall housing, which is considered the most restrictive housing and, as such, often serves as a control in exercise studies. This system inhibits normal movement and behavioural expression (Popescu *et al.*, 2013) and lessens the displays of locomotor activities, even during periods such as estrus when activity is expected to increase (Felton *et al.*, 2012). On the other end of the spectrum is pasture-based housing, which is by and far the most common housing system associated with exercise in the literature. We can qualify these two housing types as inducing the least and most locomotor activity in dairy cows and, therefore, consider these to offer the least and most amount of exercise, respectively. While other indoor and combination indoor/outdoor housing options are not as easy to subjectively rank in terms of level of locomotor activity, we can point to a number of housing-related factors that will

influence the locomotor activity in all of these housing systems: 1) the presence or absence of obstacles (e.g., stall hardware) in the environment, 2) the type of flooring the cow is exposed to, and 3) the space allotted to the cow.

2.3.1. Flooring

Flooring might be the most consequential element of dairy cattle housing as it relates to locomotor activity. Dairy cows are evolutionarily designed for pasture both physiologically and behaviourally (Knaus, 2015). Pasture epitomizes ideal flooring for dairy cattle, serving as a ‘gold standard’ for expectations regarding locomotion of cows in other housing systems. Alsaad *et al.* (2017), highlights optimal locomotor characteristics as being a shorter gait cycle and higher walking speed as well as longer stride length comprised of longer stance phases and shorter swing phases. Increasing shifts towards indoor loose-housing in recent years has stressed the importance of research into flooring alternatives to concrete, found on many farms due to its cheap cost, durability, and relatively easy upkeep (Telezhenko and Bergsten, 2005). This is of particular importance for flooring found in areas where walking and standing occurs at higher rates (e.g., milk holding areas, feed bunks, alleyways). The use of rubber mats has emerged as the most comparable flooring option to pasture applied free-stall systems (Jungbluth *et al.*, 2013), with greater compressibility (Flower *et al.*, 2007; Franco-Gendron *et al.*, 2016) and more friction created between the hoof and floor when compared to concrete (Flower *et al.*, 2007; Rushen and de Passillé, 2006). These characteristics of rubber flooring lead to an increase in walking speed (Telezhenko and Bergsten, 2005; Flower *et al.*, 2007; Chapinal *et al.*, 2011; Telezhenko and Bergsten, 2005; Alsaad *et al.*, 2017) and stride length (Telezhenko and Bergsten, 2005; Flower *et al.*, 2007; Haufe *et al.*, 2009; Franco-Gendron *et al.*, 2016; Alsaad *et al.*, 2017) when compared to concrete. In fact, stride length in loose-housing with rubber flooring was nearly the same as on

pasture (Jungbluth *et al.*, 2013). Similar results can be found with other flooring options that have the same properties as rubber mats, such mastic asphalt (Haufe *et al.*, 2009; Alsaad *et al.*, 2017).

Although free-stalls are the most implemented loose-housing system on commercial farms, stall-free systems such as compost-bedded packs and strawyards may offer even greater conditions for locomotor activity. Compared to free-stalls, there is a considerable lack of information regarding the possible impact that the walking surfaces in these environments may have on cow locomotor activity. These loose-housing systems are characterized by deep-bedded packs which offer better compressibility compared to rubber mats (Tucker *et al.*, 2009, Shepley *et al.*, 2019b). Even when implemented on smaller scales, as with the loose-pens in Shepley *et al.* (2019b), there are minor improvements to locomotor activity compared to counterparts housed in tie-stalls due to possible benefits of the deep-bedded straw on ease of movement and step quality. Options like wet, compressed sand, used in a study by Telezhenko and Bergsten (2005) as a natural, yielding surface similar to pasture, resulted in higher walking speeds and stride lengths than both rubber and concrete flooring. Woodchips in outdoor paddocks also led to more sure footing when walking as compared to the rubber flooring of an indoor free-stall, which authors O'Driscoll *et al.* (2009) attribute to the increase in exercise in the outdoor environment compared to the free-stall.

Improving aspects of cow locomotion leads to improvement in overall ease of movement within the cow's environment (Franco-Gendron *et al.*, 2016), with cows able to move more comfortably on surfaces which cushioned her step while still providing traction during each stride. This translates to increases in locomotor activity, with cows increasing step activity by nearly 1,400 steps/d on rubber flooring compared to concrete (Platz *et al.*, 2008). This may increase distances walked by over 1,000 m/d (Jungbluth *et al.*, 2013). The use of rubber flooring over concrete may also lead to improved locomotor activity in lame cows (Flower *et al.*, 2007).

Moreover, for free-stall housing, more comfortable standing and walking surfaces outside of the stall will lower cow use of the stall for standing (Haufe *et al.*, 2009), thus decreasing her likelihood of the negative consequences that come with prolonged stall confinement such as increases in injury due to more restricted ease of movement in the stall. Coupling the type of indoor flooring with pasturing allowed for cows on flooring with lower compressibility and traction indoors to still see similar improvements in stride length (Haufe *et al.*, 2008), suggesting that outdoor access may help compensate for poorer flooring conditions indoors.

There are confounding factors regarding the efficacy of flooring types to improve the cow's ease of movement and locomotor activity. Management of the walking surfaces is important to reduce slipping. Slippery floors can result in shorter stride lengths with higher step frequencies, with the increased locomotor activity coming not only at an energy cost (Telezhenko *et al.*, 2005), but possibly leading to greater stiffness in the joints as well (Herlin and Drevemo, 1997). Keeping floors free of wetness and manure necessary to reduce the slipperiness of the surface and the risk of falling and injury to the animal (Phillips and Morris, 2001). Additionally, it is difficult to disentangle the fact that leg and foot health, namely lameness and hoof lesions, impacts locomotor activity, regardless of flooring type, and that the level of locomotor activity, in turn, can impact the risk of these health issues occurring in the first place or worsening when present in a cyclical relationship, warranting further elucidation in Section 2.7.

2.3.2. Stall Hardware and space

Tie-stall and free-stall housing systems are notable for their use of stalls to delineate the individual areas for the cow to lie-down and stand. In tie-stall systems, specifically, locomotor activity is, invariably, impacted by stall hardware. Side dividers restrict the total movement that the cow can make from side to side and tie-rails place restrictions on forward movements,

increasing the risk of contact with the stalls (Boyer *et al.*, 2018; St John *et al.*, 2018) and likely limiting locomotion to more minor and less impactful movements of the feet and legs (Shepley *et al.*, 2019b). It is important to note that one of the most problematic aspects of the stall hardware and spatial restrictions of both tie-stall and free-stall housing, however, arises during the transition between standing and lying, with stall hardware and space negatively impacting ease of movement (Shepley *et al.*, 2019a) and increased risk of lameness (Zambelis *et al.*, 2018). These connections are outlined more in Section 2.8.

The removal of stall hardware and the provision of a more open space provided by loose-housing may also elicit activities that would increase overall locomotion, such as exploration of the environment (Krohn, 1994; Loberg *et al.*, 2004) and socialization with other cows (Fregonesi *et al.*, 2009). More space, overall, also resulted in more distance traveled and movements made by the cow per day in indoor housing, even when stocking density was high (Telezhenko *et al.*, 2012). Similarly, the efficiency of a pasture-based system is largely dependent on adequate room per cow (Macdonald *et al.*, 2008) which may also influence the amount of movement performed when at pasture. Although results may differ between studies for a variety of factors (e.g., pasture quantity and quality, water source location, management practices, weather), more space at pasture has been associated with more locomotor activity. Henkin *et al.* (2007) demonstrated that smaller pastures (28 ha) resulted in less walking time per day as well as around 500 steps less than larger pastures (76 and 135 ha). Anderson and Kothmann (1977) reported a similar effect of space with cows in 4 ha and 20 ha pastures walking an average of 3.6 and 5.2 km/d, respectively.

2.4. OUTDOOR ACCESS: APPLICATION ON LOCOMOTOR ACTIVITY

Alluded to multiple times in this review, several studies looking to investigate the effect of exercise on dairy cattle utilize outdoor access, either through exercise yards or pasture (e.g., Krohn

et al., 1992; Loberg *et al.*, 2004; Veissier *et al.*, 2008; Popescu *et al.*, 2013). As we saw in Table 1.2., cows that were provided with pasture access expressed greater locomotor activity than those that were not; however, connections between locomotor activity and other forms of outdoor access were less clear. Offering more space on pasture undoubtedly results in greater locomotor activity (Anderson and Kothmann, 1977; Henkin *et al.*, 2007), as does more space indoors (Telezhenko *et al.*, 2012). It could be assumed that elements affecting locomotor activity indoors could, likewise, impact locomotor activity outdoors, particularly for paddocks with harder paved surfaces (Jungbluth *et al.*, 2003) or exercise pastures with uneven and or rocky flooring. For example, Eckelkamp *et al.*(2014) saw a reduction in step activity of nearly 500 steps/d when transitioning from a free-stall with outdoor access to a compost bedded pack. As the more open area and soft flooring provided by the compost pack would be expected to positively affect step activity when compared to only a free-stall, it is possible that the elimination of this outdoor access contributed to the drop in locomotor activity. Likewise, cows housed in a deep-bedded strawyard in Shepley *et al.* (2018) took roughly 1,300 steps/d fewer than cows in Borchers *et al.* (2017) that were also housed in deep-bedded loose-housing, but were also provided constant, free access to over 3 ha of addition space in the form of an exercise pasture. It is unclear, however, if these differences are a result of outdoor access or if the space indoors and life stage (e.g., lactation in Shepley *et al.*, 2018, and pre-calving in Borchers *et al.*, 2017) contributed. When implementing the use of access to outdoor areas and pastures, it is important to consider two factors that can help or hinder their success: 1) how long and how often will access be granted? and 2) will the cows go outside when the choice is offered to them?

2.4.1. Locomotion duration and frequency: How much is enough?

When outdoor access is involved, the duration of time (e.g., number of h/d) outdoor access is applied and the frequency of access (e.g., number of d/wk) can make a considerable difference on the efficacy for increasing locomotor activity. However, the question remains: how much outdoor access does a cow need? As with addressing distances a cow must walk to achieve optimal benefits in Section 2.2, the duration of application of exercise treatments in past studies have, among other factors, been dependent on housing and stage in lactation, leading to conflicting results. Loberg *et al.* (2004), for example, indicates that 1 h/d of daily access to an exercise yard is sufficient for expression of normal levels of locomotor and other behaviours, whereas 1 h/d with less frequent access leads to compensatory inflations of these behaviors in cows. For performance benefits, 2-3 h/d is needed to benefit calving-related issues and leg health in cows (Gustafson, 1993). Health benefits, such as those measured by Keil *et al.* (2006), fall squarely between these two recommendations, indicating 50 h/month of outdoor access to be the most effective amount of outdoor access for improving hock injuries. Keil *et al.* (2006) went on to also recommend that shorter exercise periods of consistent frequency be used. This balance between duration of outdoor access and the frequency of access can have an effect on the total outcome on the cow, with a higher frequency of access with a shorter duration per day being more conducive for the improvement of issues that may require longer healing times, such as body injuries and leg health. Frequency of access may be affected by housing type. When comparing tie-stall and loose-housed cows with access to an outdoor exercise area, Regula *et al.* (2004) found more restrictive tie-stall housing, where access was generally limited to < 3 d/wk, increased risk factors (e.g., lameness, injury, restricted resting space) associated with cow health and welfare.

How outdoor access is applied also has an impact on the duration of time such access must be provided to see positive benefits. Animals with better physical fitness respond better to exercise access when provided (Blake *et al.*, 1982), so shorter daily exposure to exercise at a higher frequency of days provided per week is expected to be far more beneficial to the cow than infrequent exercise of longer durations. Indeed, when outdoor access is provided continuously, as is often seen when providing more locomotor activity through pasture housing, there is more agreement as to the benefits, especially with regard to limb health (Hernandez-Mendo *et al.*, 2007), as will be discussed in greater detail in Section 2.7, and behavior (Krohn *et al.*, 1992). This could also be due to the fact that pasture provides more space and, presumably, more opportunity for the cow to move freely (Bielfeldt *et al.*, 2005) when compared to loose-housing or exercise yards. A majority of locomotor activity on pasture is also a result of grazing (Henkin *et al.*, 2007), a behavior which is generally absent in outdoor yards, resulting in more walking when at pasture versus idling in outdoor yards. Free-access to pasture has caveats of its own to optimize use and, thus, locomotor expression, including considerations for the size of pasture (Smid *et al.*, 2018), as well as distance to pasture and pasture quality and composition (Charlton *et al.*, 2013).

Frustration behaviours during periods of increased restricted housing, be it in a tie-stall or loose-housing system, are very important to consider when offering only periodic outdoor access to dairy cows. Cows will walk nearly a quarter of a kilometer when released into an exercise yard for one hour daily, independent of any resource-seeking behaviours (Krohn *et al.*, 1992). Tethering of cows in tie-stalls, thereby restricting their ability to move freely, can be stressful for the cow (Higashiyama *et al.*, 2007). Cows that are housed for longer periods of time in tie-stalls exhibited more movement-related behaviours once released into an outdoor exercise yard (Loberg *et al.*, 2004), with as little as one day in a tie-stall resulting in more walking and trotting movements once

released than seen in cows never housed in tie-stalls (Veissier *et al.*, 2008). This suggests that cows may feel deprived of a motivation to perform movement-related activities immediately upon increased confinement. In the same vein, it indicates that the duration of time spent confined between periods of outdoor access can affect the level of locomotor activity expressed by the cow when she is once again provided with outdoor access.

When using duration/frequency of access to measure exercise in dairy cattle, it is important to keep in mind the limitations of its use. This method of measurement assumes that the cow engages in activities related to movement when provided outdoor access and may treat cows that spend a majority of their time standing idle and those that spend their time walking around to be equal in the amount of exercise they are receiving. It all comes down to the individual cow's level of locomotor activity needs as well as the cow's motivation to access and preference for pasture.

2.4.2. Motivation and individual preference for increased locomotor activity

Some humans just can't sit still and others haven't seen a day at the gym in their life. Individual levels of activity and motivation can dictate how humans approach physical activity much in the same way that it does in cows. Cows may present not only different requirements for locomotor activity based on the more apparent measures like parity, stage in lactation, or health status, but also at an individual level (Müller and Schrader, 2005). In fact, this is a primary limitation in generalized associations between locomotor activity and housing systems, particularly when providing free-access to exercise yards and pastures. Lacking the ability to anticipate future needs, animals will maximize short-term welfare over long-term welfare at nearly every opportunity afforded to them (Keeling and Jensen, 2002). Cows are no exception to this and, as such, when considering the provision of free access to pasture or outdoor exercise yards, it is crucial to keep this fact in mind. It has been theorized that dairy cows with the most to gain health-

wise from pasture may also be the cows that choose to remain indoors more frequently (Burow *et al.*, 2011), reducing the overall benefit one would expect to see for housing systems that implement a system that allows free-access pasture. Charlton *et al.* (2011) noted similar findings with cows with higher gait scores (> 1.5 , 1-5 scale where score ≥ 3 denote lameness, according to Flower and Weary, 2006) choosing to remain indoors when provided access to pasture. The same study found body condition score (BCS) to also be a contributing factor in the cow's decision to go to pasture, seeing cows with a BCS of 3 or greater going to pasture more often than those with lower BCS that may have seen the indoor environment as more immediately beneficial to their needs. It is possible that, for these animals, remaining in their indoor environment where basic needs for water, feed, and resting area can be met with limited effort may be the option that is immediately perceived as best.

Motivation and or preference to access the outdoors when presented as an option is also quite complex. Cows display fairly consistent levels of locomotor activity within their home environment (Müller and Schrader, 2005); however, this consistency of behavior isn't confined solely to their home housing system. In a study by Shepley *et al.* (2018), cows that were found to access pasture more often were also found to have higher step activity when housed in both a strawyard and a free-stall system. This suggests that individual motivation to perform locomotor activity may influence their use of additional access to pasture. Preference can also be influenced by previous experience with the outdoors. When presented with the choice between pasture and a free-stall housing option, cows without prior experience during rearing (Charlton *et al.*, 2011a) or lactation (Legrand *et al.*, 2009) expressed a lower preference for the outdoors (34 % and 54 %, respectively) when compared to cows that had more extensive experience (71 – 98 %; Krohn *et al.*, 1992, Charlton *et al.*, 2011b, Shepley *et al.*, 2017a). The role of prior experience with the

outdoors also extends to access during the winter, with cows having previous exposure to winter outdoor conditions more inclined to go outdoors during a three-hour free-choice phase (77 % vs. 38 %; Shepley *et al.*, 2017b.). Providing opportunities for outdoor access during all life stages and perhaps selecting for cows that are more suited for the outdoors will improve the overall effectiveness and viability of the provision of free-access to the outdoors as a method of increasing locomotor activity.

2.5. MOVEMENT OPPORTUNITY: REDEFINING ‘EXERCISE’ IN DAIRY CATTLE

The application of the term ‘exercise’ in most dairy cow studies is, to varying degrees, flawed and incomplete, returning us to the initial question of ‘what is exercise’ in dairy cattle. Is it the level of physical exertion made by the animal? Is it the level of locomotor activity that she engages in on a day-to-day basis? Is it providing a housing system in which the cow can move freely and express, to the degree that she chooses, locomotor activity? The authors believe it is an amalgamation of all of these definitions. It is apparent that we cannot blindly associate housing types with exercise nor can we definitively say that it is, indeed, exercise that yields the benefits to health, behavior, and comfort found in the literature. The cow’s environment provides her with the opportunity to move, hindering or promoting increased locomotor activity based on the type of housing she is exposed to, the quality and characteristics that comprises her housing, and the addition of outdoor access. This movement opportunity is dependent on not only the level of locomotor activity that the cow’s housing environment *can* provide, but on whether the individual cow *opts to utilize* the opportunity to move that she has been provided.

As the old adage goes, ‘you can lead a horse to water, but you can’t make it drink’ so, too, can a cow be provided with the means to move, but not forced to do so once placed in that environment. This change in perspective creates a more direct relationship between what we find

in research and what could be applied on-farm, particularly with regard to health, behavior, and comfort outcomes. Most importantly, it leads to an improved ability to make suitable recommendations for producers on how to adapt their housing systems to offer greater levels of movement opportunity.

2.6. MOVEMENT OPPORTUNITY AND HEALTH

2.6.1. Lameness, Limb Injury, and Hoof Health

Movement opportunity in dairy cows is associated with overall improved health, particularly with regard to hoof and leg health and incidence of lameness (Table 2.3). As mentioned previously, cows are designed for pasture, especially from the leg down. This is reflected in the reduced incidences of lameness that we see on pasture compared to indoor housing systems, particularly those that are dissimilar in flooring attributes such as stall-based systems. Benefits to gait have been found in as little as eight weeks when cows are provided with access to pasture (Hernandez-Mendo *et al.*, 2007). A ‘sound’ gait is indicative of good leg health, making it a primary method of determining lameness on loose-housed dairy farms. In the study by Hernandez-Mendo *et al.* (2007), gait significantly improved for cows kept on pasture, resulting in a shift in average gait score from ‘moderately lame’ to ‘sound’, while gait for cows kept solely in free-stall housing tended to either remain the same or worsen in this same span of time. Conversely, when access to pasture is limited to only nighttime hours over a longer period (12 weeks), gait score did not significantly differ between free-stall cows and cows with pasture access (Chapinal *et al.*, 2010). In this study, both treatment groups worsened over time, particularly after calving; however, this occurred at a slightly lesser rate in the pastured cows, suggesting some protective benefits with this limited access. The lack of effect and worsening gait can also be attributed to lower motivation to eat at night (Chapinal *et al.*, 2010), minimizing grazing behaviors that

Table 2.3. Association between hoof and leg health issues and provision of movement opportunity to dairy cows.

Category	Main Housing	Movement Opportunity	Results	P-Value	Reference
Lameness					
Prevalence, %	Tie-Stall	No outdoor access	22.2	< 0.001	Popescu <i>et al.</i> , 2013
		Daytime access to pasture/ paddock	15.1		
	Free-stall	Free-stall (normal housing)	60.9	< 0.05	Olmos <i>et al.</i> , 2009
		Pasture, indoor winter housing	17.4		
		Zero-grazing	39.1	< 0.05	de Vries <i>et al.</i> , 2015
		Summer pasture	30.5		
	Loose-housing	Compost barn	7.8	—	Barberg <i>et al.</i> , 2007
	Mixed Housing	Tie-stall, summer outdoor access, minimal winter access	19.0	< 0.001 (tie-stall, min. access vs. year-round)	Regula <i>et al.</i> , 2004
		Tie-stall, outdoor access, year-round access	14.0		
		Loose-housing, outdoor access, year-round access	11.5		
		Tie-stall, no exercise	13.2		
		Tie-stall, exercise	9.6	> 0.01 (OR)	Bielfeldt <i>et al.</i> , 2005
		Loose-housing, exercise	7.7		
		Conventional, free-stall	21.1	< 0.001 (housing type, winter); < 0.05 (system, winter)	Rutherford <i>et al.</i> , 2009
		Conventional, strawyard	15.9		
		Organic, free-stall	16.7		
		Organic, strawyard	9.9		
Leg disorders, veterinarian treatment, #	Tie-stall	Tie-stall, non-exercised	5.0	—	Gustafson, 1993
		Tie-stall, exercised 2-3 km/d	0.0		
Locomotion, scored 1 (good) to 5 (poor)	Free-stall	Free-stall (normal housing)	1.6	NS	Fregonesi and Leaver, 2001 (exp. 2)
		Strawyard	1.6		
		Confinement, no exercise	1.6	NS	Black <i>et al.</i> , 2017
		Forced exercise, 1.5 h/d, 5d/wk	1.5		
		Pasture, 1.5 h/d	1.6		
Gait change (scored 1-5), units/wk	Free-stall	Free-stall (normal housing)	-0.2	< 0.001	Hernandez-Mendo <i>et al.</i> , 2007
		Pasture access, dry period	0.1		

Category	Main Housing	Movement Opportunity	Results	P-Value	Reference
Hoof					
Sole disorder					
Severity, 1 (healthy) to 5 (severe disorder)	Tie-stall	Tie-stall, non-exercised	0.8	—	Gustafson, 1993
		Tie-stall, exercised 2-3 km/d	1.6		
Prevalence, %	Mixed Housing	Tie-stall, no exercise	16.4	NS	Bielfeldt <i>et al.</i> , 2005
		Tie-stall, exercise	16.0		
		Loose-housing, exercise	14.3		
Zero prevalence, %	Mixed Housing	Tie-stall	34.3	—	Cramer <i>et al.</i> , 2009
		Free-stall	10.5		
Laminitis					
Treatment by veterinarian, #	Tie-stall	Tie-stall, non-exercised	3.0	—	Gustafson, 1993
		Tie-stall, exercised 2-3 km/d	0.0		
Odds ratio (in relation to non-exercised group)		No outdoor access	-	0.05 - 0.1 (no access vs. 7 d/wk)	Loberg <i>et al.</i> , 2004
		1 h/d outdoor access, 1 d/wk	1.4		
		1 h/d outdoor access, 2 d/wk	1.0		
		1 h/d outdoor access, 7 d/wk	0.5		
Heel horn erosion					
Odds ratio (in relation to non-exercised group)	Tie-stall	No outdoor access	-	0.05 - 0.1	Loberg <i>et al.</i> , 2004
		1 h/d outdoor access, 1 d/wk	0.7		
		1 h/d outdoor access, 2 d/wk	0.7		
		1 h/d outdoor access, 7 d/wk	0.3		
Severity, weighted, 0-20	Free-stall	Free-stall (normal housing)	9.6	< 0.0001	Olmos <i>et al.</i> , 2009
		Pasture, indoor winter housing	5.5		
Prevalence, %	Mixed Housing	Tie-stall, no exercise	13.2	NS	Bielfeldt <i>et al.</i> , 2005
		Tie-stall, exercise	17.1		
		Loose-housing, exercise	5.0		
Zero prevalence, %	Mixed Housing	Tie-stall	34.3	—	Cramer <i>et al.</i> , 2009
		Free-stall	31.6		
Digital dermatitis					
Odds ratio (in relation to non-exercised group)	Tie-stall	No outdoor access	-	0.05 - 0.1 (no access vs. 7 d/wk)	Loberg <i>et al.</i> , 2004
		1 h/d outdoor access, 1 d/wk	2.5		
		1 h/d outdoor access, 2 d/wk	0.8		
		1 h/d outdoor access, 7 d/wk	0.6		

Category	Main Housing	Movement Opportunity	Results	P-Value	Reference
Hoof					
Severity, weighted, 0-30	Free-stall	Free-stall (normal housing)	3.8	< 0.0001	Olmos <i>et al.</i> , 2009
		Pasture, indoor winter housing	2.2		
Zero prevalence, %	Mixed Housing	Tie-stall	29.9	—	Cramer <i>et al.</i> , 2009
		Free-stall	7.9		
White line disorder					
Odds ratio (in relation to non-exercised group)	Tie-stall	No outdoor access	-	NS	Loberg <i>et al.</i> , 2004
		1 h/d outdoor access, 1 d/wk	1.1		
		1 h/d outdoor access, 2 d/wk	0.8		
		1 h/d outdoor access, 7 d/wk	0.1		
Severity, weighted, 0-60	Free-stall	Free-stall (normal housing)	17	< 0.05	Olmos <i>et al.</i> , 2009
		Pasture, indoor winter housing	14.8		
Prevalence, %	Mixed Housing	Tie-stall, no exercise	5.1	< 0.001	Bielfeldt <i>et al.</i> , 2005
		Tie-stall, exercise	5.1		
		Loose-housing, exercise	9.4		
Hemorrhages					
Severity, 0-120, weighted	Free-stall	Free-stall (normal housing)	22.9	< 0.05	Olmos <i>et al.</i> , 2009
		Pasture, indoor winter housing	15.1		
Zero prevalence, %	Mixed Housing	Tie-stall	27.6	—	Cramer <i>et al.</i> , 2009
		Free-stall	18.4		
Claw disorders					
Treatment by veterinarian, #	Tie-stall	Tie-stall, non-exercised	4.0	—	Gustafson, 1993
		Tie-stall, exercised 2-3 km/d	6.0		
Infectious, prevalence, %	Mixed housing	Tie-stall	1.8	< 0.05 (housing type, outdoor access for tie-stall)	Häggman and Juga, 2015
		Tie-stall, pasture	1.6		
		Tie-stall, pasture and winter yard	3.4		
		Loose-housing	10.3		
		Loose-housing, summer pasture	9.1		
		Loose-housing, summer pasture and winter yard	16.2		
Non-infectious, prevalence, %	Mixed housing	Tie-stall	26.4	< 0.05 (housing type, outdoor access for tie-stall)	Häggman and Juga, 2015
		Tie-stall, summer pasture	25.1		
		Tie-stall, summer pasture and winter yard	26.7		
		Loose-housing	39.2		
		Loose-housing, pasture	43.9		
		Loose-housing, pasture and winter yard	41.8		

Category	Main Housing	Movement Opportunity	Results	P-Value	Reference
Hoof					
Net claw growth					
Length, mm	Tie-Stall	No outdoor access	23.0	< 0.01 (no access vs. 7 d/wk)	Loberg <i>et al.</i> , 2004
		1 h/d outdoor access, 1 d/wk	20.4		
		1 h/d outdoor access, 2 d/wk	19.7		
		1 h/d outdoor access, 7 d/wk	15.1		
Cranial claw, length, mm	Free-stall	Confinement, no exercise	0.3	—	Black <i>et al.</i> , 2017
		Forced exercise, 1.5 h/d, 5d/wk	0.0		
		Pasture, 1.5 h/d	0.2		
Caudal claw, length, mm	Free-stall	Confinement, no exercise	1.0	—	Black <i>et al.</i> , 2017
		Forced exercise, 1.5 h/d, 5d/wk	0.2		
		Pasture, 1.5 h/d	0.2		
Injury					
Hock injury, prevalence, %	Free-stall	Zero-grazing	61.6	< 0.01	de Vries <i>et al.</i> , 2015
		Summer pasture	41.3		
	Loose-housing	Compost barn	25.1	—	Barberg <i>et al.</i> , 2007
	Mixed Housing	Tie-stall, summer outdoor access, minimal winter access	16.5	< 0.001 (tie-stall, min. access vs. loose)	Regula <i>et al.</i> , 2004
		Tie-stall, outdoor access, year-round access	13.5		
		Loose-housing, outdoor access, year-round access	5.5		
≥ 1 Lesions, prevalence, %	Tie-stall	No outdoor access	22.3	< 0.001	Popescu <i>et al.</i> , 2013
		Daytime access to pasture/paddock	10.9		
≥ 1 hairless patch, prevalence, %	Tie-stall	No outdoor access	50.5	< 0.05	Popescu <i>et al.</i> , 2013
		Daytime access to pasture/paddock	44.4		
Carpal joints callosities, prevalence, %	Mixed Housing	Tie-stall, summer outdoor access, minimal winter access	62.5	< 0.01 (tie-stall, min. access vs. loose)	Regula <i>et al.</i> , 2004
		Tie-stall, outdoor access, year-round access	58.5		
		Loose-housing, outdoor access, year-round access	10.5		

comprises a majority of outdoor locomotor activity (Henkin *et al.*, 2007). Additionally, a combination of increased access to movement opportunity with the prolonged exposure to pasture in the first study and the potentially confounding effect of predominantly housing cows indoors in the second led to the discrepancies found in gait.

When reviewed across epidemiological analyses investigating the application of outdoor exercise for dairy cows, we see more evidence of the beneficial effects of increasing movement opportunity on prevalence of lameness. Popescu *et al.* (2013) reported a higher mean percentage of lame cows in tie-stall housing without exercise when compared to those that received an average of 10.7 h/d for 182 d/y on pasture (22.2 vs. 15.1 %, respectively; $P < 0.001$). In similar studies, we find lameness prevalence drops by 3.5 – 5 % in tie-stall cows with regular outdoor access and 5.5 – 8.0 % in loose-housed cows with regular outdoor access when compared to cows housed solely in tie-stalls (Regula *et al.*, 2004; Bielfeldt *et al.*, 2005). From this, it is evident that time outside of the otherwise permanent indoor housing has been linked to marked improvement on the prevalence of lameness; however, simply providing a primary indoor housing system that releases the cow from her stall does not guarantee an improvement in leg health. For instance, both Regula *et al.* (2004) and Bielfeldt *et al.* (2005) showed greater improvement to lameness in loose-housed cows, but to a lesser extent than the improvement yielded from the increase in movement opportunity afforded to them by the outdoor access.

Furthermore, there is considerable debate over the difference in lameness prevalence between tie-stall housing, a system that provides no movement opportunity to the cow, and free-stall housing, which provides continuous free-access to movement opportunity. In a study by Cook (2003), free-stall cows displayed a higher prevalence of lameness than tie-stall cows under two different stall bedding, even though the housing system theoretically provides more opportunity

for movement to the cow. This returns to the discussion of the quality of movement opportunity provided. Ill-suited or poorly designed housing can lead to higher incidences of lameness (Häggman and Juga, 2015), which would limit the effect that any increased movement opportunity would have on cows in a loose-housing system. Strawyards have been found to have a lower incidence of lameness when compared to free-stalls ($P < 0.05$, Haskell *et al.*, 2006). Compost bedded packs have also been reported to have a low prevalence of lameness (7.8 %, Barberg *et al.*, 2007; 4.4 vs. 13.1 and 15.9 %, compost-pack vs. two different free-stall systems; Lobeck *et al.*, 2011), suggesting that these stall-free housing environments offer better conditions for the cow.

Leg health and the cow's locomotor abilities are determined by an amalgamation of factors relating to not only lameness, but to leg injuries and hoof health as well. Previous studies in which cows were provided with increased movement opportunity resulted in a reduction of injuries (e.g., -13.4 %, $P < 0.001$, Popescu *et al.*, 2013), particularly of the hock (Keil *et al.*, 2006), and of incidences of non-infections hoof issues (Loberg *et al.*, 2004, Charlton *et al.*, 2010). Lower prevalence of injury was found in housing systems with larger, more open lying surfaces that better imitate pasture conditions such as strawyards (e.g., 0.49 vs. 0.15 scratched hocks out of score 2, free-stall vs. strawyard, respectively; Haskell *et al.*, 2006) and compost barns (3.8 % vs. 23.9 and 31.2 %, compost-pack vs. two different free-stall systems; Lobeck *et al.*, 2011) than in free-stall housing. Providing a deep-bedded pack which offers a denser, more compressible lying surface, may also reduce knee and hock lesions and swelling to a prevalence that matches what is found on pasture (de Vries *et al.*, 2015). It is arguable, however, that, with regard to injury, it is more a comment on environmental characteristics of the housing system than it is on the movement opportunity provided.

Similarly, hoof health may be better associated with more comfortable footing on pasture than with the increased ability to move around on pasture. Non-infectious hoof health issues were found to be 11 % lower for cows provided access to pasture than for those kept indoors in a free-stall (Chapinal *et al.*, 2010); however, the infectious hoof issues, such as dermatitis, were found to be four times more likely to occur in cows provided more access to an outdoor exercise pasture than their indoor counterparts (odds ratio = 0.64 vs. 2.53, 1 vs. 7 days of access/wk, Loberg *et al.*, 2004). Infectious hoof diseases are targetable through increased sanitation and foot bath use, especially in transfer areas leading out to exercise yards or pasture. Increased movement does have some direct benefits to hoof health, though, as it is associated with increased blood flow the legs that improves hoof health (Bielfeldt *et al.*, 2005). Additionally, increasing movement opportunity by providing access to an outdoor yard may benefit net claw growth, with overall net growth reduced as exercise frequency is increased (Loberg *et al.*, 2004), decreasing discomfort and foot issues from overgrown claws between hoof trimmings.

2.6.2. Reproduction

Both on a physiological level (e.g., uterine involution, Lamb *et al.*, 1979; dystocia, Popescu *et al.*, 2013) and with regard to estrus detection, providing less restrictive housing environments has been shown to improve reproductive ability in the cow. This increase in movement opportunity to the cow can reduce the number of treatments for health-related issues post-calving, especially in the first two weeks of the new lactation (Gustafson, 1993) which is a crucial transition period for the cow that can have lasting health and production implications throughout the subsequent lactation (Drackley, 1999). Conception rates showed numeric improvement when cows were moved to more open housing systems such as compost barns (+3.3 %, Barberg *et al.*, 2007) and when they were housed on pasture (+9.8 % compared to free-stall, Washburn *et al.*, 2002),

suggesting minor reproductive advantages. Whether this is attributable to the physiological state of the cow as a reflection of increased movement opportunity or has other underlying causes rooted in factors such as management is not evident.

There is a tendency towards a lower number of services required to achieve conception and fewer days open for cows that receive exercise during the prepartum period, particularly for later parity cows, that has been attributed to improved fitness of the cow (Lamb *et al.*, 1981). Both the number of inseminations needed to achieve conception and the rate of conception is also related to the cow's increased ability to perform estrus-related behaviours in less restrictive environments. For example, in tie-stalls, cows in estrus do not exhibit a change in activity (Felton *et al.*, 2012). Time provided outside of the tie-stall may improve rates of accurate estrous detection, which is important for determining when to breed cows and missed heats may result in increased days open or failure to conceive if inseminated too late. Heat detection is similarly reduced in free-stall-housed cows compared to pasture (Palmer *et al.*, 2010), suggesting that movement opportunity as well as ease of movement for displaying estrous behaviors is hindered by certain loose-housing characteristics as well. Thus, movement benefits not only the cow's health during and after pregnancy, but also the producer's ability to better detect when the cow is most receptive to pregnancy.

2.6.3. Udder Health

Mastitis is caused by either contagious bacteria, spread primarily through teat-to-teat contact during milking, or environmental bacteria, which can multiply and spread rampantly through many vectors in the cow's environment. Immunosuppression can lead to increased susceptibility to mastitis, with the highest risk just after calving (Drackley, 1999). Exercise increases physical condition and fitness (Blake *et al.*, 1982.; Davidson and Beede, 2009) which

may benefit immune response, thus helping to combat the bacterial infection. Cows provided exercise on pasture have been found to have significantly lower instances of mastitis than tie-stall cows (Popescu *et al.*, 2013) and free-stall cows (Washburn *et al.*, 2002). When targeted during the dry period, cows provided as little as two weeks on pasture reduced the odds of clinical mastitis occurring in the first 30 days of the subsequent lactation (Green *et al.*, 2010), during which time cows are generally more vulnerable to health issues (Gustafson, 1993). Connections between prevalence levels of mastitis must be considered with caution as mastitis is heavily associated with the environment which can differ between housing types as well as between different farms with the same housing system. This is true for all systems, be they tie-stall, loose-housing, or pasture-based. For instance, level of exercise provision did not appear to significantly affect incidence of mastitis in either tie-stall or loose-housed cows (Regula *et al.*, 2004), where reduced ability to avoid contaminants may lead to increased risk in both housing systems. This makes management, as much as the level of movement opportunity, consequential when regarding risk of mastitis.

2.6.4. The Physiology of Fitness

Much like a well-trained athlete, cows show a physiological response to exercise, increasing in fitness with increased exposure. Measures of red blood cells, such as erythrocytes and hemoglobin, are sensitive indicators of physical fitness and increase in as little as eight weeks of exercise (Blake *et al.*, 1982). In humans, higher concentrations of red blood cells are found in trained athletes (Mairbäurl, 2013), which allows for more efficient circulation of oxygen to the tissues. Measurement of plasma lactate concentration, found to be 28 % (2.7 vs. 3.7 mmol/L; Davidson and Beede, 2003) to over 50 % lower (1.4 vs. 3.2 mmol/L, Davidson and Beede, 2009) in cows exercised for the same 8-wk period compared to those that were not, may be an additional indicator of fitness. Reduced plasma lactate concentrations are associated with improvements in

the body's ability to attain homeostasis (Davidson and Beede, 2009). A final blood component that may be beneficial to consider in relation to the cow's physical condition are glucocorticoids such as cortisol. Glucocorticoids play a regulatory role in energy metabolism and exercise performance capacity (Hackney and Walz, 2013). Unconditioned heifers showed elevated levels of glucocorticoids during and just after being exercised; however, after an 8-wk training period, the same heifers did not require a substantial increase in glucocorticoids to maintain homeostasis during or after exercise (Arave *et al.*, 1987), suggesting an increase in fitness.

Increasing fitness through increasing movement may both lower the cow's resting heart rate and reduce the magnitude of increase in heart rate when exercise is applied (Davidson and Beede, 2003), indicating an improvement to cardiovascular ability. Arave *et al.* (1987) found a reduction in the magnitude of heart rate elevation during exercise after an eight-week training period; however, this study did find pre-exercise heart rate to be higher. Heart rate is responsive to the application of exercise, rapidly rising during the onset of exercise, but also fluctuation due to factors unrelated to exercise (Blake *et al.*, 1982) and thus should be used with caution. Respiration rate may be an equally sensitive option to use for determining the impact of exercise on cow fitness. Heifers exercised for eight weeks had significantly lower post-exercise respiration rates than they had initially, indicating that they were less challenged by the same exercise regimen after conditioning and may have been more physically fit (Arave *et al.*, 1987). Blake *et al.* (1982) reported minor reductions in respiratory rate in cows after eight weeks of exercise at a moderate distance, but found increased rates when cows were walked for long distances, suggesting that there is a threshold for movement that should be considered.

2.7. MOVEMENT OPPORTUNITY AND COW LYING BEHAVIOR

Certain behaviours are important for biological functions. For instance, dairy cow will typically spend between 10-14 h/d lying down (Ito *et al.*, 2009), making it a key indicator in dairy cattle health and welfare (Vasseur, 2015). Deviations from normal lying behavior can be affected by cow health (e.g., lameness, Walker *et al.*, 2008), chronic stress (Ladewig and Smidt, 1989), and housing conditions (e.g., cubicle design, Fregonesi *et al.*, 2009; lying surface, Tucker *et al.*, 2009). Deprivation of the normal expression of such behaviours, as is increasing common in dairy cows confined to indoor housing, may have a considerable effect on an animal's physiology and, in turn, overall health (Moberg, 1985).

Cows housed indoors in free-stalls only (Hernandez-Mendo *et al.*, 2007) and those in a free-stall with access to an outdoor exercise area (Dohme-Meier *et al.*, 2014) spent more time lying than their counterparts on pasture, with lying time incrementally increasing as housing became more restrictive (Table 2.4). Lying bouts, however, are higher on pasture than in free-stalls (15.3 bouts/d vs. 12.2 bouts/d, $p < 0.001$, Hernandez-Mendo *et al.*, 2007). Fewer lying bouts has been associated with a lower ease of standing and lying-down movements in more restrictive environments (Haley *et al.*, 2000). Rest quality may be likewise benefited by housing systems that offer greater movement opportunity, with 26 and 54 % synchronicity of lying behaviours found in pasture-based housing, yet only 17 and 26 % synchronicity has been reported in tie-stall and deep-bedded pack systems, respectively (Krohn *et al.*, 1992). Behavior is more synchronized as a whole at pasture than in alternative indoor forms of housing (Krohn *et al.*, 1992), possibly due to the ability of pasture to sufficiently meet the resource needs of the animal which, in turn, reduces interruption of lying from agonistic interactions (Fregonesi and Leaver, 2001).

Table 2.4. Lying behaviours and their association with housing types that offer varying levels of movement opportunity to the cow.

Measure	Main Housing	Treatment	Results	P-Value	Reference
Lying Time					
Avg. h/d	Tie-stall	Large pen (individual box stall)	14.7	< 0.001	Haley <i>et al.</i> , 2000
		Tie-stall (normal housing)	10.5		
		Tie-stall, dry period (normal housing)	13.0	NS	Shepley <i>et al.</i> , 2019
		Deep-bedded pen, dry period	14.4		
		Tie-stall, standard (normal housing)	11.2	NS	Boyer <i>et al.</i> , 2018
		Tie-stall, double-width	11.9		
	Free-stall	Free-stall (normal housing)	12.7	< 0.01	Fregonesi & Leaver, 2000 (exp. 1)
		Strawyard	13.6		
		Free-stall (normal housing)	13.0	< 0.05	Fregonesi <i>et al.</i> , 2009
		Open pack	12.5		
		Free-stall (normal housing)	12.3	< 0.01	Hernandez-Mendo <i>et al.</i> , 2007
		Pasture access, dry period	10.9		
		Small area, high density	13.4	< 0.05	Telezhenko <i>et al.</i> , 2012
		Small area, low density	13.7	(density);	
		Large area, high density	13.9	NS (size)	
		Large area, low density	14.2		
		Access to outdoor exercise area	10.3	< 0.05	Dohme-Meier <i>et al.</i> , 2014
		Pasture access	9.7		
		Free-stall	11	NS	Black & Krawczel, 2016
		Pasture	9.5		
		Free-stall (normal housing)	11.9	NS	Shepley <i>et al.</i> , 2018
		Strawyard	11.6		
	Free-stall, pasture access	Free-stall, pasture access	9.4	N/A	Eckelkamp <i>et al.</i> , 2014
		Compost Pack	13.1	N/A	
	Free-stall, summer pasturing	Pre-confinement (day -1 and -2)	10.5	< 0.05	Enriquez-Hidalgo <i>et al.</i> , 2018
		Early confinement in tie-stall (d 3)	7.5	(early vs. all other;	
		Late confinement in tie-stall (d 10)	9.5	late vs. post)	
		Post-confinement (d 13-14)	10.8		

Measure	Main Housing	Treatment	Results	P-Value	Reference
Lying Bouts					
Bout frequency, #/d	Tie-Stall	No exercise	11-13	NS	Gustafson & Lund-Magnussen, 1995
		2-3 km/d over 2-3-h period	10-14		
		Tie-stall (normal housing)	8.2	< 0.01	Haley <i>et al.</i> , 2000
		Large pen (individual box stall)	13.6		
		Tie-stall, standard (normal housing)	13.5	< 0.05	Boyer <i>et al.</i> , 2018
		Tie-stall, double-width	12.1		
	Free-stall	Free-stall (normal housing)	15.3	< 0.001	Hernandez-Mendo <i>et al.</i> , 2007
		Pasture access, dry period	12.2		
		Free-stall (normal housing)	11.4	< 0.001	Olmos <i>et al.</i> , 2009
		Pasture-housing, dry period	8.1		
		Small area, high density	10.8	NS (size, density)	Telezhenko <i>et al.</i> , 2012
		Small area, low density	10.5		
		Large area, high density	10.2		
		Large area, low density	10.1		
		Free-stall	9.5	NS	Black and Krawczel, 2016
		Pasture	10		
		Free-stall (normal housing)	9.6	< 0.01	Shepley <i>et al.</i> , 2018
		Strawyard	10.4		
	Free-stall, summer pasturing	Pre-confinement (day -1 and -2)	8.5	< 0.05	Enriquez-Hidalgo <i>et al.</i> , 2018
		Early confinement in tie-stall (d 3)	11.5		
		Late confinement in tie-stall (d 10)	14.0		
		Post-confinement (d 13-14)	6.5		
Bout duration, min/bout	Tie-stall	Tie-stall (normal housing)	86.7	NS	Haley <i>et al.</i> , 2000
		Large pen (individual box stall)	68.0		
		Tie-stall, standard (normal housing)	54.0	< 0.05	Boyer <i>et al.</i> , 2018
		Tie-stall, double-width	60.0		
	Free-stall	Free-stall (normal housing)	50.3	< 0.001	Olmos <i>et al.</i> , 2009
		Pasture-housing, dry period	39.3		
		Free-stall	75	NS	Black and Krawczel, 2016
		Pasture	70		

Measure	Main Housing	Treatment	Results	P-Value	Reference
Bout duration, min/bout					
	Free-stall, summer pasturing	Pre-confinement (day -1 and -2)	90.0	< 0.05	Enriquez-Hidalgo <i>et al.</i> , 2018
		Early confinement in tie-stall (d 3)	55.0		
		Late confinement in tie-stall (d 10)	65.0		
		Post-confinement (d 13-14)	113.0		
Lying synchronization					
All cows lying down, min/d	Free-stall	Free-stall (normal housing)	107.5	< 0.01	Fregonesi and Leaver, 2000 (exp. 1)
		Strawyard	56.0		
≥ 10 cows lying down, # of 15-min periods/d	Mixed Housing	Tie-stall	17.0	< 0.01	Krohn <i>et al.</i> , 1992
		Deep-bedded pack	36.0		
		Pasture	54.0		
Lying-down Behavior					
Collisions when lying-down, %	Tie-stall	Tie-stall, dry period (normal housing)	50.0	< 0.01	Shepley <i>et al.</i> , 2018
		Deep-bedded pen, dry period	9.9		
		Tie-stall, standard (normal housing)	77.1	< 0.05	Boyer <i>et al.</i> , 2018
		Tie-stall, double width	43.1		
		No exercise access	44.57	< 0.001	Popescu <i>et al.</i> , 2013
		Exercise access	21.07		
Duration of lying movement, median/event, s		No exercise	46-70	< 0.01	Gustafson and Lund-Magnussen, 1995
		2-3 km/d over 2-3-h period	30-36		
		No outdoor access	29.43	NS	Loberg <i>et al.</i> , 2004
		1 h/d outdoor access, 1 d/wk	35.06		
		1 h/d outdoor access, 2 d/wk	24.01		
		1 h/d outdoor access, 7 d/wk	31.23		
		No exercise access	6.77	NS	Popescu <i>et al.</i> , 2013
		Exercise access	5.41		
Duration of lying movement, avg/6 event, s		Tie-stall, dry period (normal housing)	6.5	NS	Shepley <i>et al.</i> , 2019
		Deep-bedded pen, dry period	5.6		

Measure	Main Housing	Treatment	Results	P-Value	Reference
Duration of lying movement, avg/6 event, s		Tie-stall, standard (normal housing)	6	NS	Boyer <i>et al.</i> , 2018
		Tie-stall, double width	5.9		
Abnormal lying-down, avg/6 events, %		Tie-stall, dry period (normal housing)	69.7	< 0.01	Shepley <i>et al.</i> , 2019
		Deep-bedded pen, dry period	18.3		
		Tie-stall, standard (normal housing)	51.4	NS	Boyer <i>et al.</i> , 2018
		Tie-stall, double width	38.9		
Rising Behavior Collisions when rising, avg/6 events, %	Tie-stall	Tie-stall, dry period (normal housing)	10.0	NS	Shepley <i>et al.</i> , 2019
		Deep-bedded pen, dry period	13.3		
		Tie-stall, standard (normal housing)	41.0	NS	Boyer <i>et al.</i> , 2018
		Tie-stall, double width	38.2		
Duration of rising movement, avg/6 event, s		Tie-stall, dry period (normal housing)	9.2	NS	Shepley <i>et al.</i> , 2019
		Deep-bedded pen, dry period	6.2		
		Tie-stall, standard (normal housing)	9.5	NS	Boyer <i>et al.</i> , 2018
		Tie-stall, double width	7.0		
Abnormal rising, avg/6 events, %		Tie-stall, dry period (normal housing)	50.8	NS	Shepley <i>et al.</i> , 2019
		Deep-bedded pen, dry period	39.7		
		Tie-stall, standard (normal housing)	56.3	NS	Boyer <i>et al.</i> , 2018
		Tie-stall, double width	51.4		
Delayed normal rising, mean %	Mixed Housing	Tie-stall, summer outdoor access, minimal winter access	33.00	NS	Regula <i>et al.</i> , 2004
		Tie-stall, outdoor access, year-round access	26.00		
		Loose-housing, outdoor access, year-round access	29.00		

The ability to transition between standing and lying with ease has been investigated in a number of different housing environments that restrict movement at varying levels. This is due, in part, to the presence of stall hardware (Shepley *et al.*, 2019) found in tie-stall and free-stall systems leading to more collisions with the confines of the environment, but also a result of space provided in each environment. Providing more room for lying in the form of a loose-pen (Shepley *et al.*, 2018) and by doubling stall width (Boyer *et al.*, 2018) minimize the effects of contact with elements of the environment such as stall dividers (30 % reduction in collisions, double-width stall; Boyer *et al.*, 2018) and pen wall (40.1 % reduction, loose-pen, Shepley *et al.*, 2019), increasing ease of movement in these animals. Cows in these enlarged environments are able to move more easily between different lying postures, particularly regarding the ability to extend their hind legs out without disturbing the neighboring cow (Boyer *et al.*, 2018; Shepley *et al.*, 2018).

Apart from the housing characteristics, however, we still find evidence of improvement derived from increasing the movement opportunity for the cow. The provision of outdoor access to tie-stall cows for 1 h/d in a study by Gustafson and Lund-Magnussen (1995) nearly halved the amount of time it took the cow to rise compared to cows that remained tethered throughout the study, even though stall conditions in both cases were the same. This same affect can be found on the time it takes the cow to lie-down, with considerable differences found between pasture (19 s), a bedded-pack (59 s), tie-stall cows with 1 h/d of outdoor access (118 s), and tie-stall only cows (123 s). Pasture and bedded-packs should offer similar larger, hardware-free lying area with a more compressible lying surface, yet we see large differences in the time it takes the cow to lie down. Environments that restrict movement may lead to the deterioration of the cow's physical condition (Krohn and Munksgaard, 1993), particularly with regard to joint health (Gustafson and Lund-

Magnussen, 1995). Furthermore, environments that affect lying-down and rising ability has been correlated with incidence of lameness and injury (Zambelis *et al.*, 2018) which can negatively affect locomotor ability in the cow. Thus, the benefits of housing that offers greater movement opportunity are two-fold: it increases the odds of improving overall health and fitness and it also provides a comfortable environment in which the cow can move with increased ease.

2.8. CONCLUSION

Movement opportunity, whether through direct application, such as forced movement of the cow, or through the application of housing types associated with greater levels of movement opportunity, has numerous benefits to dairy cow health, behavior, performance, and welfare, warranting its consideration when establishing housing recommendations in the dairy industry. Pasture may be the most suitable option for cows in theory. It provides ample, open space with good walking surfaces which increases the total movement of the cow and offers increase area and choice for lying, enhances normal behavioural expression, and has many associated health benefits, particularly with regard to lameness. However, it may not be an option for all producers and, for many who are able to put this housing system into practice, may not be feasible year-round. Consideration for indoor housing and how housing characteristics and designs can influence movement opportunity in the cow can provide all producers with the ability to incorporate some form of access to their current housing and management, particularly where stall-based housing is concerned. Improving indoor housing conditions, such as lying area, flooring type, and cubicle-free housing, can compound the benefits of pasture. There is still much to be confirmed regarding the ways in which the cow's environment affects her opportunity to move. Similarly, affirmation of other benefits to areas such as production, general health, and cow longevity which may result from increased movement opportunity is required to understand the full extent of the impact that

housing and management has on the cow. To address these research gaps, however, one thing is certain: it is about time we redefine our view of ‘exercise’ in dairy cattle as what it is – the provision of an environment in which she has the greatest opportunity to move – to keep dairy cows happy, healthy, and, of course, in motion.

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Connecting Statement 1

To measure locomotor activity in dairy cows we must first ensure that the methods by which these measurements are taken are accurate. Cow movements are not only more restricted in tie-stall housing, but also different with regard to the amplitude of these movements compared to loose-housing settings. IceRobotic's Ictag and IceQube leg-mounted pedometers are, perhaps, the most frequently referenced brand of pedometers in dairy cattle studies. While these devices have seen validation in loose-housing settings, they, and many other activity monitors, lack validation for their use in tie-stalls. This posed an issue both for our study and for any research looking to provide comparative data on locomotor activity involving these pedometric devices.

Furthermore, movements in tie-stall housing do not necessarily require the equal movement of both legs, as is more common when walking in loose-housing and pasture-based systems. For instance, a cow would be more inclined to move a single foot forward and then back again, equalling two steps by traditional pedometer readings on a single foot, as she is restricted to only the stall's width and length to move. Contrast this with loose-housing, where the cow has a greater ability to and likelihood of moving both legs more equally, as she would when walking. As such, we needed to: 1) define what a 'step' movement constitutes in a tie-stall system, 2) ensure that the pedometer worked in a tie-stall system, comparing step activity from the pedometer to that observed in video recordings, 3) test to make sure that the number of steps recorded on the left and right leg of the cow were not statistically different from one another. This required additional validation to confirm that step data obtained by the pedometer would not be biased by the foot on which the pedometer was mounted. As a result, the first study conducted as a part of this PhD thesis, presented in the following chapter, outlines how we define a step in a tie-stall system, and

demonstrate the validation of the accuracy of step activity recorded in tie-stall housed dairy cows by IceTag pedometers, regardless the leg on which leg it is mounted.

**CHAPTER 3 — *TECHNICAL NOTE: VALIDATION OF THE ABILITY OF A 3D
PEDOMETER TO ACCURATELY DETERMINE THE NUMBER OF STEPS TAKEN
BY DAIRY COWS WHEN HOUSED IN TIE-STALLS***

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3.1 ABSTRACT

The automation of farm tasks in dairy production has been on the rise, with an increasing focus on technologies that measure aspects of animal welfare; however, such technologies are not often validated for use in tie-stall farms. The objectives of the current study were to (1) determine the ability of the IceTag 3D pedometer to accurately measure step data for cows in tie-stalls, and (2) determine whether the leg on which the pedometer is mounted impacts step data. Twenty randomly selected Holstein dairy cows were equipped with pedometers on each rear leg and recorded for 6 h over three 2-h periods. Two observers were trained to measure step activity and the total number of steps per minute were measured. Hourly averages for right and left leg data were analyzed separately using a multivariate mixed model to determine the correlation between pedometer and video step data as well as the correlation between left and right leg step data. The analysis of the video versus pedometer data yielded a high overall correlation for both the left ($r = 0.93$) and right ($r = 0.95$) legs. Additionally, there was good correlation between the left and right leg step data ($r = 0.80$). These results indicate that the IceTag 3D pedometers were accurate for

calculating step activity in tie-stall housed dairy cows and can be mounted on either leg of a cow. This study confirms that these pedometers could be a useful automated tool in both a research and commercial setting to better address welfare issues in dairy cows housed in tie-stalls.

Keywords: Automation; dairy cow; pedometer; validation study

3.2. INTRODUCTION

In recent years, the adoption of automation within the dairy industry has increased, changing how cows are milked (e.g., robotic milkers), fed (e.g., automatic feeding systems), and monitored (e.g., ear-, collar- or leg-mounted activity monitors). Greater attention is being paid to production animal welfare, increasing the need for more precise, automated methods of measuring welfare. Lying time, assessed by activity monitors such as pedometers, is one of the most commonly used outcome measure of dairy cow welfare (Vasseur *et al.*, 2017). Step activity, also measured by these devices, may have its own application in welfare monitoring, particularly with regard to lameness detection (O’Callaghan *et al.*, 2003). The application of automated technologies on dairy farms can be dependent on the type of housing used. Tie-stall housing, as a primary example, inhibits movement ability in dairy cows, restricting the physical and behavioural indicators that can be used by farmers to detect early signs of illness or monitor heat. This is particularly true in the implementation of activity monitoring through pedometers. Step activity for various types of pedometer technologies have been previously validated, primarily targeting use in loose-housing (Higginson *et al.*, 2010) and pasture (Elischer *et al.*, 2013). Felton *et al.* (2012) provides, to the author’s knowledge, the only currently available insight on the applicability of pedometers in tie-stall housing systems, and their study found that the AfiMilk pedometers, when compared to observation videos of step activity, accurately measured step activity in tie-stall housed cows. The objective of the current study was to validate the accuracy of the IceTag 3D

pedometer (IceRobotics, Edinburgh, UK) in measuring step activity in tie-stall housed dairy cows. This study also sought to determine if the leg on which the pedometer is mounted (i.e., either the right or left leg) effects the step data measurement.

3.3. MATERIALS AND METHODS

Twenty tie-stall housed Holstein dairy cows were randomly selected from the McGill University Macdonald Campus Dairy Complex (Ste-Anne-de-Bellevue, QC, Canada) for use in the study. Cows ranged in parity (mean $\pm$ SD and range: 2.75 ± 0.99 , 1–5) and stage of lactation (DIM (days in milk) mean $\pm$ SD and range; 123.6 ± 115.45 , 2–432). Prior to the start of the validation process, leg mounted 3D accelerometers (HOBO Pendant G Acceleration Data Logger, Onset Computer Corp., Pocasset, MA, USA), set to record at 1-min intervals, were attached to the rear leg of eight randomly selected cows for a period of seven days to identify three 2-h periods of time where long bouts of standing were common and activity was likely to be high. The three selected 2-h periods were 10:00 to 12:00, 14:30 to 16:30, and 19:00 to 21:00.

Two different cows were recorded daily for three pre-determined 2-h recording periods using two camcorders (JVC GZ-E100BU AVCHD 40X Optical Zoom, Konica Minolta HD Lens 116 mm 1:1.8, Mississauga, ON, Canada; JVC GZ-R10BU AVCHD 60X Dynamic Zoom, Konica Minolta HD Lens 116 mm 1:1.8, Mississauga, ON, Canada), amounting to 6 h of video recording per cow (120 h total). The camcorders were placed in the alley behind the cows and positioned to ensure that the feet remained in sight for the duration of the recording periods. Before the first 2-h recording period, the cows were equipped with two IceTag 3D pedometers, mounted on to the left and right rear legs of the cows. The exact start time, starting on the minute, was recorded prior to each of the three recordings for all 20 cows. Following each recording day, the pedometers were removed and placed on a new cow. Data from the pedometers were extracted weekly.

Video recordings were reviewed by a single observer. The observer reviewed the 6 h of video recording for each cow, counting the total number of steps observed each minute. The definition of a step was determined by reviewing second by second pedometer data and corresponding video recordings. In a similar study investigating step activity in tie-stall housed cows, a step was defined as when the rear foot lifted completely off the ground and was returned to the ground in any location with or without moving the entire body (Felton *et al.*, 2012). In the initial review of the videos, it was found that it was not necessary for the foot to lift off the ground and, as such, an additional component to this definition of a step was added. In addition to when the foot completely leaves the ground, a step was also counted when the foot moves quickly (<1 s) and at a distance roughly equivalent to two hoof lengths or more in any direction without leaving the ground. The observer was trained to observe for step activity with a secondary observer also trained in the same manner to ensure that the observation process was reliable and repeatable between observers. Inter-observer reliability calculated using a weighted Kappa coefficient as $K_w = 0.82$. Intra-observer repeatability was also calculated using a weighted Kappa coefficient as $K_w = 0.88$ and 0.86 for observer 1 and 2, respectively.

3.4. STATISTICAL ANALYSIS

The analysis was run on hourly step averages for both the pedometer and observation data. Pedometer step data for the left leg of two cows were excluded due to technological error and, as such, only 18 cows were used in the analysis of left step data. Left and right leg pedometer data were analyzed separately using a multivariate mixed model with the number of steps as a dependent variable and technology and time as fixed effects. Data was run in SAS (version 9.4, SAS Institute Inc., Cary, NC, USA) using PROC MIXED to obtain covariance estimates from which correlation between observation and pedometer data could be computed. The same

multivariate mixed model was used to obtain estimates to calculate the correlation between the left foot and the right foot with step as the dependent variable and leg and time as the fixed effects.

3.5. RESULTS AND DISCUSSION

The average number of steps recorded in the 6-h observation period and the corresponding average number of steps recorded by the IceTag 3D pedometer for both the left and right leg can be found in Table 3.1.

Table 3.1. Mean $\pm$ SD, minimum, maximum, and median of the total number of steps performed by the selected tie-stall housed cows in the 6-h recording period for the left and right leg of both the pedometer output and observation video results.

Leg	Step Measurement	Mean $\pm$ SD	Minimum	Maximum	Median
Left	Pedometer	196.4 $\pm$ 75.2	51	354	194
	Observation	219.1 $\pm$ 74.0	103	380	179.5
Right	Pedometer	221.5 $\pm$ 89.2	63	383	228.5
	Observation	239.3 $\pm$ 94.3	84	436	238

The number of steps recorded by the pedometer was found to be highly correlated with the observed number of steps from the video recordings for both the left leg ($r = 0.93$) and the right leg ($r = 0.93$), indicating the pedometer's accuracy in measuring step activity in tie-stall housed dairy cows. These findings are in line with those of Felton *et al.* (2012), which found a similarly high correlation ($r = 0.88$) between video recordings and the AfiMilk pedometers to accurately measure step activity in tie-stall housed cows. It was expected that the IceTag 3D pedometer would yield similar accuracy, as step activity for the AfiMilk pedometer had been previously validated against the IceTag 3D pedometer in a free-stall housing system and was found to have similar outputs ($r = 0.82$; Higginson *et al.*, 2010).

The number of steps recorded by the pedometer on the left leg was also well correlated with the number of steps recorded by the pedometer on the right leg ($r = 0.80$). Good correlation between the pedometers on the two legs suggests that the leg on which the pedometer is mounted is not important in ensuring the reliability of the output, necessitating fewer pedometers to accurately measure cow step activity in tie-stall setups. This has important implications, particularly in the monitoring of dairy cow activity both in a research setting and on commercial farms. The use of a single pedometer requires less monetary investment and therefore increases the accessibility of the technology for end-users.

Step activity, measured by the pedometer, may have the potential to be a means of early detection of lameness in dairy cows. Lameness is one of the leading causes of involuntary culling of dairy cows (Langford *et al.*, 2012) and, as such, automated methods for the early detection of lameness would have considerable benefits to both the cow and the producer. Lying time, an additional measure recorded by most pedometers, is a commonly used indicator of cow welfare, with health issues such as lameness leading to alterations in the amount of time cow spends lying down (Vasseur, 2017). In tie-stalls, however, an epidemiological study of 100 tie-stall herds found no relationship between lying measures (total lying time, bout frequency, or mean bout duration) and prevalence of lameness (Charlton *et al.* 2016). As noted in Vasseur (2017), a wide range of individual variation coupled with additional environmental and physiological factors influence the ability of lying time, on its own, to be entirely reliable for detecting lameness. Similarly, step activity has been linked to lameness, as step activity was found to be significantly decreased in lame cows compared to non-lame cows ($p < 0.001$) in free-stall systems (O’Callaghan *et al.*, 2003). As with lying time, a large variation between individuals has been found to be a potential issue with the use of step activity as an indicator of lameness (Mazrier *et al.*, 2006). Coupling both

aspects of the pedometer technology may have the potential to increase the ability of pedometers to detect lameness in tie-stall housed cows; however, further research is necessary to confirm this assertion.

This study found that IceTag 3D pedometers are indeed accurate in recording step activity in tie-stall housed dairy cows. Furthermore, the results from the left and right leg data yielded similar results, allowing for the pedometer to be attached to either rear leg without compromising the step data obtained. Ensuring the validity of the pedometer's application in tie-stall systems opens this technology's use up to new possibilities in future research, particularly in lameness detection for tie-stall housed dairy cows.

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Connecting Statement 2

As was established in Chapter 1, it is possible to influence the opportunity of movement provided to the cow through either changes in her housing system or with additional access to alternative housing at select periods of time. One such period of time is the dry period, a time during which the cow is no longer being milked and when her only job is to maintain or, in many cases, regain her health and physical condition. This study selected a deep-bedded loose-pen, representative of a strawyard or other deep-bedded pack option, as this is a housing method for dry cows that is not uncommon on commercial farms, but is seldom investigated with regard to the benefits that it may offer to the cow.

Two most substantial benefits that housing associated with increased movement opportunity appears to provide for dairy cows, regardless of lactation stage, are related to her lying behaviours and to her leg health. The following two chapters will layout the benefits that providing tie-stall dairy cows with a deep-bedded straw loose-pen during an 8-wk dry period has on lying time, lying postures, and rising and lying ability (Chapter 4), as well as cow gait (Chapter 5). Chapter 5 will also present the connection that these benefits may have to the level of movement opportunity provided by this change of dry-cow housing by recording locomotor activity using IceTag pedometers. In Chapter 2, the IceTag pedometer was shown to be accurate in measuring step activity in tie-stall-housed dairy cows, allowing for its use in determining the level of locomotor activity that the cows in each housing environment express in this study. Chapter 5 delves deeper into these locomotor activity results, utilizing the information regarding the definition of a step presented in Chapter 2 to also discuss how not only the quantity of steps taken may be influenced by the level of movement opportunity provided through the cow's housing, but that the characteristics within the environment may influence step quality as well.

CHAPTER 4 — THE EFFECT OF HOUSING TIE-STALL DAIRY COWS IN DEEP-BEDDED PENS DURING AN EIGHT-WEEK DRY PERIOD ON LYING TIME, LYING POSTURES, AND RISING AND LYING-DOWN BEHAVIOURS

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4.1 ABSTRACT

Dairy cow lying behavior is useful in determining the cow's level of welfare and also in determining how her environment may affect her comfort and ease of movement. In tie-stall systems, cows usually remain in a stall for the length of their lactation. The dry period offers a unique opportunity to provide alternative housing to the cow with minimal impact on farm housing and management. Our objective was to determine if housing tie-stall cows in deep-bedded pens over an 8-week dry period altered lying time, lying and rising ability, and lying postures. At dry-off, 20 cows paired by parity and calving date were randomly assigned to a deep-bedded loose-pen (LP) or a tie-stall (TS). Leg-mounted pedometers measured lying time. Rising and lying ability was measured using six events of rising and lying from 24-hr video recordings taken 1x/wk/cow. Sequenced images (1/min) from the 24-hr recordings were used to document lying postures and locations for each cow. Data was analyzed for the early (first week of dry-off), mid, and late (week prior to calving) term of the dry period. Lying time did not differ between LP and TS, but was

numerically higher for LP than TS cows (14.4 vs. 13.0, respectively). Contact with stall/pen confines when lying-down was 5-fold higher in TS than LP. The increased contact coupled with a higher occurrence of hindquarter shifting in the late term led to higher overall abnormal lying behaviours in TS. Contact with the stall upon rising increased in the late term for TS cows. LP cows also exhibited greater variation in hind legs postures, keeping legs tucked 20% less often in favor of alternative postures. Stall hardware (e.g., tie-rail, dividers) may have affected the ease of transition between lying and standing, leading to higher levels of contact with the stall. LP cows are able to assume more postures than TS cows when provided more space, possibly allowing her to orient herself in a way that provides greater comfort. Lying surface in the deep-bedded loose-pen may ease the cow's lying-down and rising movements and lead to the higher lying time found with LP cows. Overall, aspects of the stall largely contributed to differences in lying behaviours, warranting further studies into whether free-stall systems would yield similar outcomes. Improving our concept of ease of movement related to lying and quality of rest in dairy cows through evaluating lying behaviours in different housing systems allows for better recommendations on viable alternative housing options.

Keywords: Dry cow; ease of movement; housing; lying behavior

4.2 INTRODUCTION

Cows place a high value on access to lying (Cooper *et al*, 2007) with cows on commercial farms typically spending between 9 and 13 h/d lying down (Ito *et al*, 2009). Indeed, cows exposed to just 2- and 4-hour lying deprivation spent less time feeding once deprivation conditions were removed in order to recover lost lying time (Cooper *et al*, 2007). Deviations from normal lying behaviours amongst individual cows have also been linked with several potential health issues, such as severe injury (Zambelis *et al*, 2018), lameness (Walker *et al*, 2008), and mastitis (Medrano-

Galarza, 2012) as well as potential issues with the general comfort of the cows lying surface (Tucker *et al*, 2009) and cubicle design (Fregonesi *et al*, 2009). For this reason, lying time has often been a key indicator of health and welfare status in dairy cattle research (Vasseur, 2017).

There are a number of factors, from the moment the cow indicates her intentions to lie down to the time she rises back up again, that may be indicative of the cow's level of comfort relative to her lying area and the ease with which she can lie down, change lying postures, and rise. The ability to transition between lying and standing, for instance, has been found to be correlated with not only physical welfare indicators such as lameness and injury but also with the size of the cow relative to her environment (Zambelis *et al*, 2018). Housing systems that are more restrictive, such as those with standard-sized stalls, impede on cow rising and lying-down ability when compared to stalls doubled in width (Boyer *et al*, 2018) and with strawyard housing systems that lack stall hardware entirely (Fregonesi *et al*, 2009). During the time that the cow is lying, her posturing of her body, head, and limbs and use of her lying area may suggest her general level of comfort. Boyer *et al*.(2018) found that, when provided with a greater surface area for lying, cows utilized more lying postures, particularly with regard to the posturing of the legs.

While strawyards appear to be more advantageous to the expression of cow lying behaviours, a majority of cows reside in housing systems that utilize cubicles and tie-stalls remain a prevalent housing system in the dairy industry, with over 74 % (CDIC, 2017) and 34 % (USDA, 2014) of cows in Canada and the United States, respectively, housed in tie-stalls. The dry period offers a unique opportunity to provide alternative housing, with minimal impact on the existing housing system and on-farm management, for dairy cows normally housed in tie-stalls during the course of her lactation, as the cow no longer needs to be at the stall for daily milkings. The cow's environment can also have a significant impact on her overall welfare, especially during the dry

period, as the cow undergoes a number of physiological changes and is managed differently than the lactating herd. The dry period is, therefore, an ideal time to investigate the impact of taking the cow out of the stall and to investigate different housing types that may better meet the needs of prepartum cows.

In the current study, we sought to determine if housing tie-stall dairy cows in a deep-bedded loose-pen during an 8-week dry period 1) increased the amount of time the cows spent lying down and 2) improved ease of movement when lying through the ability to use different lying postures and when transitioning between lying and standing.

4.3 MATERIALS AND METHODS

4.3.1 Ethics Statement

A certified Animal Care Committee of McGill University and Affiliated Hospitals Research Institutes reviewed and approved the use of animals in this project and all procedures (#2016-7794). All aspects of this study meet the high standards established by the Canadian Council on Animal Care to ensure the continued humane and ethical use of animals in research.

4.3.2 Animals and Treatments

This study was conducted at the Macdonald Campus Dairy Unit of McGill University (Sainte-Anne-de-Bellevue, Quebec). A total of 20 primiparous and multiparous Holstein cows were enrolled between August 2016 and March 2018 as they entered their dry period. Cows were blocked based on expected calving date and parity (mean $\pm$ SD = 2.1 ± 1.00 and 2.6 ± 1.42 ; range = 1-4 and 1-6; tie-stall and loose-pen, respectively). Three cows were removed from the analysis due to reasons unrelated to the treatment: one due to aborting her calf at the start of the dry period, one that was dried off prematurely, and a third due to poor temperament that hindered safe handling of the cow. This resulted in a total of nine cows in the loose-pen treatment and eight cows in the

tie-stall treatment used in the analysis. The cows in each of the paired groups were randomly allocated to one of the two treatment options: loose-pen (LP) or tie-stall (TS). The start date for each pair was staggered over the course of the study from September 2016 to December 2017. Cows were dried off and enrolled eight weeks before their expected calving date; however, the mean amount of time between dry-off and calving for this study was 8.34 weeks for tie-stall (range: 7.29 – 9.86) and 7.51 weeks for loose-pen (range: 6.57 – 8.71). Cows in the LP treatment calved in their experimental pens. Cows in the TS treatment were moved to a calving pen when the barn staff observed physical signs of imminent calving (mean 3.63 d before calving, range 0-12 d). Physical signs included bagging up of the udder, mucosal discharge and/or swelling of the vulva, and changes in behaviours (e.g., restlessness, decreased appetite). After calving, both LP and TS cows were moved back to a tie-stall housing system.

4.3.3 Housing and Management

Before enrollment in the study, all cows were housed in tie-stalls. The deep-bedded loose-pen housing was comprised of four individual pens measuring 3.35 m x 4.88 m (16.35 m² total) each. Pens were bedded with straw to 20.0 cm in depth with a base of concrete topped with 1.9 cm thick rubber mats (Ani-Mats, Ani-mat Inc., Sherbrooke, QC, Canada). A thin layer of lime was applied onto of the rubber mats before bedding was placed. Each pen was fitted with a feed bin (Stack-N-Nest, LewisBins+, Oconomowoc, WI, USA) measuring 38.4 cm H x 76.5 cm W x 60.96 D and a water bowl. The tie-stall housing consisted of stalls measuring 1.41 m x 1.87 m in width and length, respectively. Stalls were bedded with 2.0 cm of wood shavings on a 4.4 cm pasture mat base (KKM longline; Distribution Multi-Mat, Inc. Ste-Cécile-de-Milton, QC, Canada). A single water bowl was shared between every two stalls. Both the loose-pen and tie-stall housing systems were designed to either meet or exceed current recommendations set by the Dairy Code

of Practice (Dairy Farmers of Canada-National Farm Animal Care Council, 2009). Compressibility of the lying surface for both treatments was measured once during the trial using a 10 kg Clegg hammer (Clegg impact soil tester; Lafayette Instrument Company, Lafayette, IN, USA). The average compressibility of the stall base with 2 cm of bedding was 5.18 CIV/H (Clegg impact value/heavy hammer) and average compressibility of the deep-bedded loose-pens was 4.85 CIV/H. Lower values indicate higher compressibility.

Tie-stalls were cleaned frequently as per routine management with any contaminants removed when seen by passing barn staff (avg. 15 passes/d). Fresh wood shavings were added daily to maintain 2 cm of bedding throughout the course of the study. Loose-pens were cleaned once in the morning with fresh bedding added to maintain a 20.0 cm depth of bedding. Pens were also spot-cleaned once daily in the evening to remove any visible manure. All cows were fed two different rations during the course of the study: a far-off and a close-up TMR. An average of 21.1 kg/d of far-off TMR was fed from the start of dry-off to three weeks prior to expected calving and was comprised of 48.0 % hay, 46.7 % silage, 4.3 % protein supplement, and 1.0 % vitamin and mineral supplement. An average of 24.6 kg/d of close-up TMR was fed from three weeks prior to expected calving to the date of actual calving and was comprised of 17.2 % hay, 69.0 % silage, 9.0 % protein supplement, 4.4 % energy supplement, and 0.4 % vitamin and mineral supplement. Rations were fed once in the morning at approximately 07:00 h. Hay was fed ad libitum to cows during the dry period.

4.3.4 Measures

Lying time.

Total lying time was recorded continuously throughout the dry period using a 3D pedometer (IceTag™, IceRobotics, Edinburgh, Scotland) attached to a rear leg of the cow.

Pedometer data was retrieved weekly. Data was output in one-minute intervals that were summed per day and sum of each day was then averaged by week. Lying times were analyzed for the early (first week of dry-off), mid, and late (last week before calving) terms of the dry period.

Lying-down and rising behaviours.

Twenty-four-hour observation video recordings were captured with an overhead camera (Smart Turret 2.8 (TS) and Fish Eye Camera (LP), Hikvision, Leavy, Canada) for cows in both treatment groups. Recordings were taken once per week on the same day for each cow over the course of the study, and were used to measure behaviours related to lying-down and rising behaviours and lying postures. Cow lying-down and rising behaviours were measured using the methodology outlined by Zambelis *et al.*(2018) in which 6 separate events of lying and of rising, four during the day and two at night, were selected randomly from the total events captured over each 24-h video recording period. From each of the six selected events, eight lying-down behaviours were recorded: intention movements before lying down, duration of lying motion, contact with the environment, attempts of lying, hindquarter shifting, dog sitting, lying on left or right side, and overall abnormal lying (Table 4.1). Similarly, seven rising behaviours were recorded: total duration of rising event, contact with the environment, shuffling back on carpal joints, delayed rising, attempts of rising, horse rising, and overall abnormal rising (Table 4.2). All lying-down and rising behaviours are presented in the results as the average of the six selected events from each 24-h video recording.

Table 4.1. Description of lying-down behaviours and sampling units, evaluated for tie-stall (TS) and loose-pen (LP) treatments¹

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

¹Based on Zambelis *et al.*(2018)

²Adapted from Zambelis *et al.*(2018)

³Binary classification with 'Yes' and 'Left' scored as 1 and 'No' and 'Right' are scored as 0

Table 4.2. Description of rising behaviours and sampling units, evaluated for tie-stall (TS) and loose-pen (LP) treatments¹

Behavior	Sampling Unit	Behavior
Duration of rising motion ²	Seconds	Length of time required to complete the lying motion Start of motion: cow is in a sternal position, situated to propel itself forward End of motion: cow gathers its forelimb side by side on the stall bed (tie-stall) or pen surface (loose-pen)
Contact with environment ²	Yes or no ³	While cow propels itself forward (with both carpal joints on the ground), its head or neck touches the tie-rail (tie-stall) or pen wall (loose-pen)
Backward movement on carpal joints	Yes or no ³	When resting on carpal joints, cow moves its front leg(s) backward before or after propelling itself
Delayed rising	Yes or no ³	Cow rests on carpal joints for > 10 s
Attempts of rising	Number of attempts	The number of attempts required to successfully complete the rising motion Failed lying attempt: Cow propels itself forward from the sternal position without successfully rising; can appear as a forward and back motion
Horse rising	Yes or no ³	Cow gets up first with front legs, then with hind legs
Overall abnormal rising	Yes or no ³	Cow requires > 1 attempt to rise and/or is scored as 'Yes' for contact with environment, backward movement on carpal joints, delayed rising, and/or horse rising

¹Based on Zambelis *et al.*(2018)

²Adapted from Zambelis *et al.*(2018)

³Binary classification with 'Yes' scored as 1 and 'No' are scored as 0

classifications were reported as a percentage of the number of times (labeled as the % occurrence)

that the behaviours were recorded to have occurred across these six events.

Lying and rising behaviours were recorded for the early, mid, and late terms of the dry period. Observations of these behaviours were recorded by three observers with inter-observer

reliability and intra-observer repeatability ranges recorded at $K_w = 0.61-1.00$ and $K_w = 0.88-1.00$, respectively, for lying-down behaviours and $K_w = 0.64-1.00$ and $K_w = 0.81-1.00$ for inter-observer reliability and intra-observer repeatability ranges, respectively, for rising behaviours.

Lying postures and location.

Based on the procedure by Boyer *et al.*(2018), a multimedia framework video editing software (FFmpeg 4.0, 2000) was used to extract sequenced images of from each 24-h video recording, producing a single image per minute for use in 1-min instantaneous scan sampling of lying postures and locations of the cow when lying (1,440 images/cow/week). Images in which the cows were lying down were reviewed by two trained observers. A description of the lying postures can be found in *Table 4.3*. Locations of the head and limbs were reported for cows housed in the TS treatment (*Table 4.4*; *Figure 4.1*).

For cows in the LP treatment, pens were divided into four quadrants with characteristics of each quadrant the same for each pen (*Figure 4.2*). Quadrant 1 was characterized by a shared divider with the adjoining pen and the water bowl, quadrant 2 shared an open divider with the adjoining pen and held no other resources, quadrant 3 had no adjoining pen and held the feed bin, and quadrant 4 also had no adjoining pen and was by the pen entrance. The cow was recorded as being in a quadrant when more than 40% of her length was in that quadrant. As such, a cow could be recorded as being in more than one quadrant at the same time. Postures and locations were analyzed for the early, mid, and late terms of the dry period and results were presented as a mean percentage of time each posture and location were recorded for all lying instances during a 24-h recording period. Inter-observer reliability and intra-observer repeatability percent agreement were recorded at 93.3 % (range: 83.3 – 100 %) and 92.5 % (range: 83.3 – 100 %), respectively.

Table 4.3. Ethogram with a description of observed postures, by body part, measured during lying for tie-stall (TS) and loose-pen (LP) treatment cows¹

Category	Posture	Description
Side	Left or Right	The side on which the cow is resting, either her left or right flank is against the ground
Body	Lying on Sternum	The body is resting on the ground
	Lying on Side	The body is resting flat on one side with the legs of the supported underside extended and the head resting on the ground
Head	Upright	Cow is lying on the sternum, the head is raised off the ground
	Back	Cow is lying on the sternum, the head is positioned towards the posterior of the cow with the head resting against the body
	Ground	Cow is lying on the sternum or side, the head is stretched resting on the floor
Front Leg	Tucked	Front leg is tucked under or to the side of the body (full plantar-flexion at the humoral joint)
	Extended	Front leg is extended in front of or to the side of the body
Hind Leg	Tucked	Hind leg is positioned at an angle of fewer than 45 degrees in relation to the body axis or underneath the body
	Extended	Hind leg is positioned at an angle of 90 degrees or greater in relation to the body axis
	Mid-position	Hind leg is positioned at an angle between 45 and 90 degrees in relation to the body axis

¹Based on Haley *et al*, 2000

Table 4.4. Description of the observed locations of cow limbs and head in relation to the stall environment (Figure 4.1) for tie-stall (TS) housed treatment cows when lying down

Body Part	Location	Description
Head	Divider	The head is resting on the stall divider
	Manger	Muzzle is encroaching on the manger area (beyond the stall-manger border) ¹
	Stall	Muzzle is behind the stall-manger border, within the borders of the stall bed ¹
	Neighbor's Stall	Muzzle is encroaching on the neighboring cow's stall (beyond the stall divider)
Front Leg	Manger	Front leg extends over the manger wall and into the manger area (beyond the stall-manger border)
	Stall	Front leg is behind the stall-manger border, within the borders of the stall bed
	Neighbor's Stall	Front leg extends into the neighboring cow's stall (beyond the stall divider)
Hind Leg	Stall	Hind leg is positioned within the borders of the stall bed
	Neighbor's Stall	Hind leg extends into the neighboring cow's stall (beyond the stall divider)
	Alleyway	Hind leg extends outside of the stall bed, encroaching on the alleyway (beyond the stall's curb)

¹Adapted from Haley *et al*, 2000

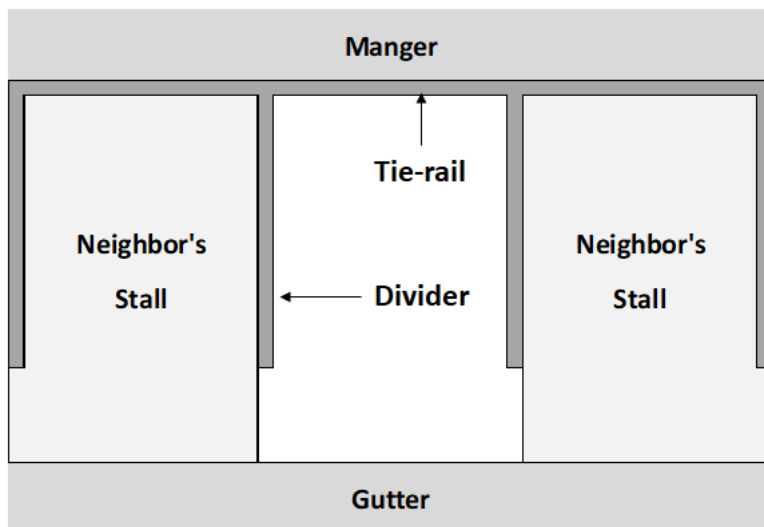


Figure 4.1. Locations in and around the stall environment used for observing the location of the limbs and head for tie-stall (TS) housed treatment cows when lying down

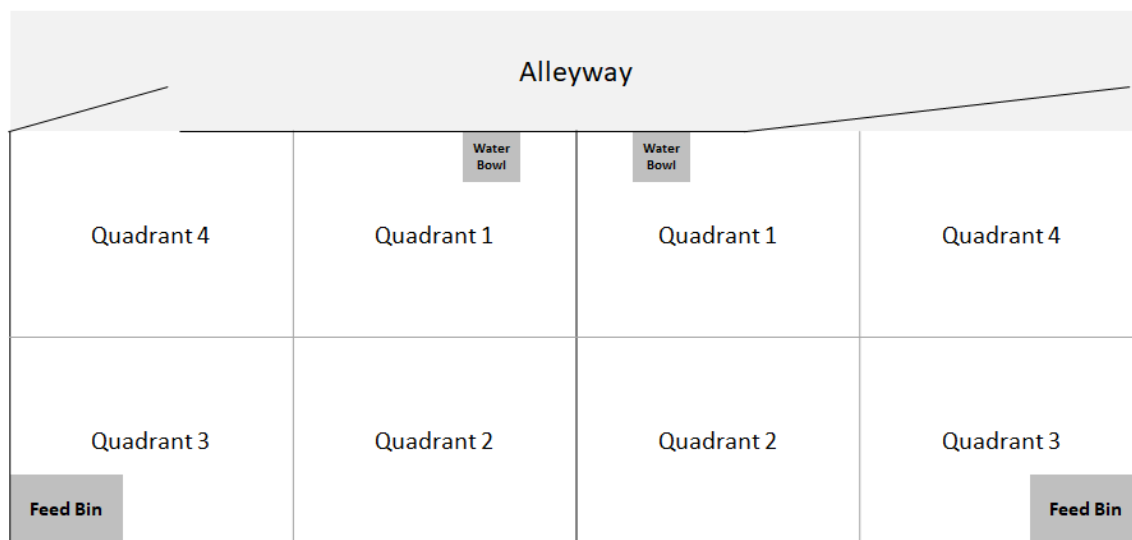


Figure 4.2. A depiction of the division of the loose-pen environment into four quadrants for use in recording the lying locations of loose-pen (LP) treatment cows when lying down

4.3.5 Statistical Analysis

All analyses were run in a statistical analysis software, SAS 9.4 (SAS Institute, 2008) and were conducted at the cow level using a mixed model procedure (PROC MIXED and LSMEANS), following the model:

$$\gamma_{ijkm} = \mu + \text{Treatment}_i + \text{Block}_j + \text{Cow}_{jk} + \text{Term}_m + \text{Treatment}_i \times \text{Term}_m + e_{ijkm}$$

where γ_{ijkm} represents the observation, μ is the population mean, treatment_i is the fixed effect of the i^{th} treatment (TS, LP), block_{ij} is the fixed effect of the j^{th} block (1-10), cow_{jk} is the random effect of the k^{th} cow in the j^{th} block (1-2), term_m is the fixed effect of the m^{th} term (early, mid, late), and e_{ijkm} represents the residual error. Repeated measures for term were analyzed using two relevant covariance structures: compound symmetry and autoregressive lag 1 (Supplementary Table S4.1). Scheffé's adjustment was used to account for multiple comparisons in the analysis of term and the interaction between treatment and term. Normality was tested against the residuals for all variables using the PROC UNIVARIATE and PROC MIXED procedures. Horse rising and dog sitting were not observed to have occurred and thus could not be run by the analytical software and were excluded from analysis. The analysis for locations in which postures were recorded for both tie-stall and loose-pen were run separately and therefore did not have treatment as a fixed effect but otherwise followed the same statistical analysis process as the other variables.

4.4. RESULTS

4.4.1 Lying time

There was no significant difference in lying time between TS and LP treatments (12.97 ± 0.63 vs. 14.43 ± 0.58 h/d, respectively; denominator degrees of freedom (ddf) = 5.95, F-value = 2.22, $P = 0.15$; Supplementary Table S4.3). There was an effect of term ($P < 0.05$), with lying time increasing over the course of the dry period for both TS and LP cows. However, once multiple

comparisons were accounted for, only tendency was retained between lying time in the early and mid terms of the dry period (+0.76 and +0.79 h/d for TS and LP, respectively; $P = 0.07$).

4.4.2 Lying-down Ability

The duration of the intention time before lying down was five seconds longer for LP cows than for TS cows (Table 4.5; $P < 0.05$). Additionally, there was an effect of term on intention time, with both treatments requiring a higher duration of time to decide to lie-down in the mid (+1.16 s and +3.56 s for TS and LP, respectively) and late term (+7.09 s and +10.67 s) compared to the early term. Contact with the confines of the cow's housing environment when lying down was higher for TS cows than for LP ($P < 0.01$), with contact occurring more than 5-fold more often in the tie-stalls. The occurrence of hindquarter shifting was higher at the end of the dry period than the beginning and middle ($P < 0.05$), with a tendency for a higher occurrence of hindquarter shifting in TS cows in the late term compared to the mid term (+27.08 %, $P < 0.1$). Overall abnormal lying was found to occur 3.8 times more often in TS cows than their LP counterparts ($P < 0.01$), with the higher occurrence of hindquarter shifting and contact found in TS cows being the leading contributors to this significance.

4.4.3 Rising Ability

There was no difference between treatments on any measured behaviours related to the cow's ability to rise (Table 4.6). While not significant, there was a numerically longer time to rise for TS cows compared to LP cows (9.2 s vs. 6.2 s; $P = 0.12$). There was a treatment-x-term effect for contact with the confines of the cow's housing environment when rising ($P < 0.05$), with the percentage of times when cows made contact increasing over 10 % by the end of the dry

Table 4.5. Lying-down behaviours reflecting the cows' ability to transition from standing to lying when housed in a Tie-Stall (TS) or Loose-Pen (LP), presented as a treatment mean $\pm$ S.E, averaged across the early, mid, and late term

Behavior	Treatment, Mean $\pm$ S.E		Difference of LSMEANS	Ddf	F-Value	P-Value
	TS	LP				
Intention Time (s)	19.70 $\pm$ 1.50	24.79 $\pm$ 1.36	5.09 $\pm$ 2.06	10.00	6.13	0.03
Time to Lie Down (s)	6.56 $\pm$ 0.75	5.60 $\pm$ 0.67	-0.95 $\pm$ 1.02	6.00	0.86	0.48
Attempts to Lie Down (no. of attempts)	1.01 $\pm$ 0.01	1.00 $\pm$ 0.01	-0.01 $\pm$ 0.01	4.90	0.79	0.42
Hindquarter Shifting (% occurrence)	24.25 $\pm$ 8.49	8.54 $\pm$ 7.65	-15.71 $\pm$ 11.67	6.00	1.81	0.27
Contact (% occurrence)	49.87 $\pm$ 7.65	9.64 $\pm$ 6.90	-40.23 $\pm$ 10.51	6.47	4.66	< 0.01
Overall Abnormal Lying (% occurrence)	70.30 $\pm$ 9.35	18.14 $\pm$ 8.43	-52.16 $\pm$ 12.85	6.15	16.49	< 0.01

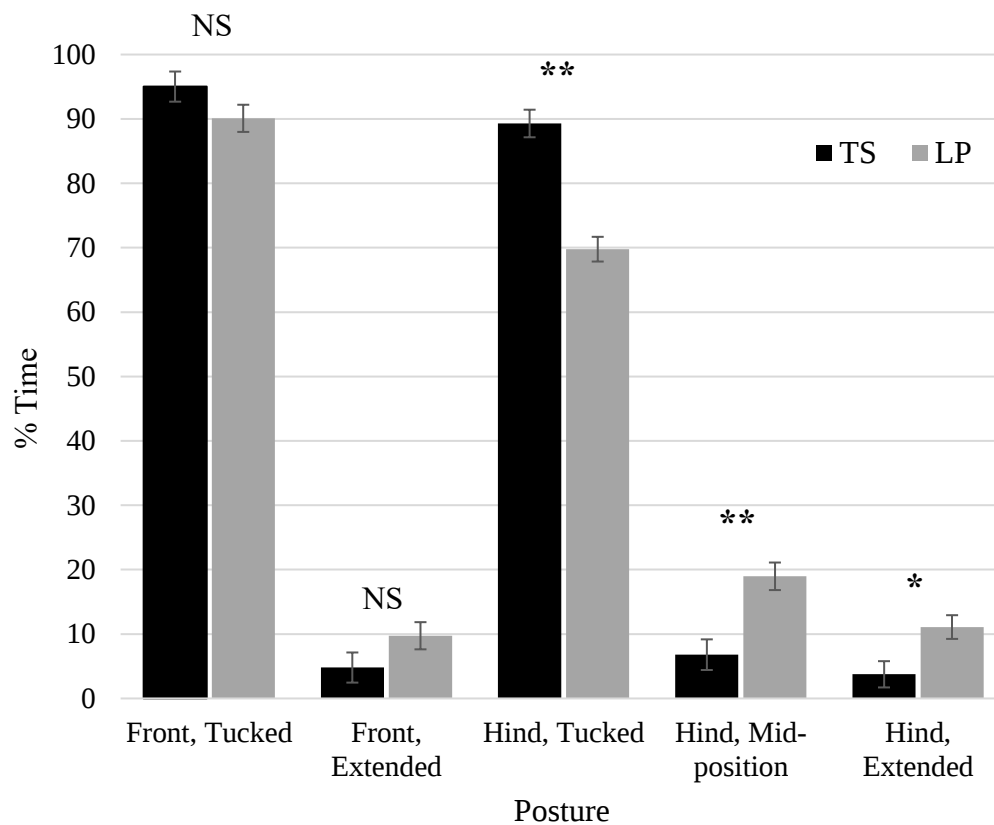
Table 4.6. Rising behaviours reflecting the cows' ability to transition from lying to standing when housed in a Tie-Stall (TS) or Loose-Pen (LP), presented as mean $\pm$ S.E., averaged across the early, mid, and late term

Behavior	Treatment, Mean $\pm$ S.E		Difference of LSMEANS	Ddf	F-Value	P-Value
	TS	LP				
Time to Rise (s)	9.17 $\pm$ 1.18	6.23 $\pm$ 1.06	-2.95 $\pm$ 1.62	6.06	3.29	0.12
Contact (% occurrence)	10.02 $\pm$ 7.25	13.27 $\pm$ 6.53	3.25 $\pm$ 9.95	6.00	0.11	0.75
Delayed Rising (% occurrence)	6.98 $\pm$ 5.90	-0.16 $\pm$ 5.32	-7.14 $\pm$ 8.11	6.00	0.78	0.46
Rising Attempts (no. of attempts)	1.81 $\pm$ 0.30	1.24 $\pm$ 0.27	-0.56 $\pm$ 0.42	6.45	1.82	0.25
Backward on Knees (% occurrence)	17.05 $\pm$ 4.67	8.16 $\pm$ 4.21	-8.89 $\pm$ 6.41	6.51	1.92	0.23
Overall Abnormal Rising (% occurrence)	50.83 $\pm$ 11.24	39.72 $\pm$ 10.12	-11.11 $\pm$ 15.44	6.00	0.52	0.50

period for TS cows and decreasing by over 6 % for LP cows (+10.41 % vs. –6.29 % for change between early and late term for TS and LP, respectively).

4.4.4 Lying Postures and Locations

Cows housed in the LP treatment for the duration of the dry period apportioned their lying time more evenly between the three different hind leg postures, with 20 % less time spent with the hind legs tucked when compared to TS cows (69.77 ± 1.92 % vs. 89.29 ± 2.14 %, respectively; $P < 0.01$; Figure 4.3).



*Significance at a p-value < 0.05

**Significance at p-value < 0.01

Figure 4.3. The percentage of time spent in a tucked, extended, or mid-position for the front and hind leg postures, presented as the mean value, for tie-stall (TS; black) and loose-pen (LP; gray) housed treatment cows. Error bars represent the SEM.

LP cows also spent more time than TS cows with their hind legs in the mid-position (18.97 ± 2.14 % vs. 6.80 ± 2.38 %; $P < 0.01$) and extended postures (11.09 ± 1.84 % vs. 3.75 ± 2.04 %; $P < 0.05$). Cows in the LP tended to position their heads upright less often than TS cows (91.25 ± 0.39 % vs. 92.51 ± 0.43 %, respectively; $P = 0.05$), instead spending more time resting their heads towards the back (8.32 ± 0.58 % vs. 6.38 ± 0.64 %; $P = 0.07$).

There was no significant difference between the time spent lying in any of the four quadrants in the LP treatment; however, cows spent numerically more time in quadrant 2 (46.0 % for quadrant 2 vs. 23.8 - 28.3 % for quadrants 1, 3, and 4; $P = 0.16$). In the TS treatment, use of different locations in and around the stall (e.g., gutter, stall, neighbor's stall) was not affected by term. When in the mid-position and extended position, the TS cow's hind legs were found to be in a neighboring stall 65.54 ± 7.01 % (mean $\pm$ S.E., range = 0 – 100 %) and 79.26 ± 5.12 % (range = 0 – 100 %) of the time, respectively. When the front leg was in the extended position, it was observed to be in the neighbor's stall 16.11 ± 5.20 % of the time (range: 0 – 100 %).

4.5 DISCUSSION

A number of factors relating to housing characteristics of the two treatment areas may have contributed to the differences found in lying behaviours in the current study. Particularly with regard to lying-down and rising ability, the presence of stall hardware appeared to have a considerable impact. Contact with the tie-rail when rising increased for TS cows during the late dry period, suggesting that these animals may experience a reduction in ease of movement when rising. The tie-rail has been shown to be a point of contact for cows when rising and a possible explaining factor for welfare concerns such as neck injury in the cow (Bouffard *et al*, 2017). Cows housed in deep-bedded loose-pens, conversely, showed a numeric decrease in contact over the course of the dry period, suggesting that cows adapt to their environment and learn to avoid the

contact within her environment whereas tie-stall cows have less opportunity to do so. St John *et al.*(2018) attributed a 14.3 % reduction in contact with the tie-stall over a ten-week period for lactating cows to adaptation to their treatment stalls with most of the reduction (-11.1 %) observed by the mid-point of the study. However, results for tie-stall cows in the current study found the opposite occurred, necessitating further research into stall hardware options for dry cows in tie-stall housing (e.g., more flexible material to absorb part of the force applied during contacts).

Perhaps more severe with regard to impeded movement by stall hardware was the level of contact with the stall dividers during the lying-down movement, with cows coming in contact with the confines of the stall around half of the time. Larger cows have been found to be more affected by stall confines, with a study by Zambelis *et al.*(2018) finding that larger cow widths were positively correlated with increases in contact with the stall confines when lying down. In similar studies, contact decreased over time by 6.3 % (Boyer *et al*, 2018) and 21.6 – 50.6 % (St John *et al*, 2018) compared to the 10 % numeric increase seen in our study. While the current study did not account for cow girth, cow size may have increased during the dry period by comparison to the beginning of the study as a result of progressing gestation. Hindquarter shifting may have been used by TS cows in the late term of the dry period, where there was a tendency for TS cows to increase in hindquarter shifting by nearly 3-fold, as a means to adjust her body to avoid collisions with environmental impediments. Increasing the width of the stall is one method for improving ease of movement within the stall, particularly for larger cows and cows housed in tie-stalls during the dry period. For instance, distancing the cow from stall dividers by doubling stall width can lead to similar reductions in contact with the cow's environment when lying down (-34 %, Boyer *et al.*, 2018), improving overall ease of movement when lying down. When eliminating the stall all

together as we did in the LP treatment of our current study, an even greater reduction in environmental collisions is achieved.

Cow preference for lying area within her environment is also a method for determining how the environmental characteristics affect the cow. In our study, loose-pen cows had no difference in lying location but did numerically utilize quadrant 2 most frequently. This is notable as this quadrant was devoid of resources (i.e. water bowl, food bin, doorway) which may reduce space available in other quadrants and may disrupt the cow when transitioning between lying and standing. This may also be evident in the higher intention time in the LP cows' lying-down behavior by comparison to TS cows, which is contrary to previous studies on lactating cows which show that more space results in a lower intention time (e.g., pasture vs. tie-stall; Krohn and Munksgaard, 1993; tie-stall with double width stall to vs. tie-stall with normal width; Boyer *et al*, 2018). It is possible that the cows in our study were more discerning in their choice of lying area and, as a result, initiated longer intention movements before deciding where to lie down than TS cows where choices were limited.

Alluded to when discussing the presence/absence of stall hardware is another defining feature which differentiates the tie-stall treatment area from that of the loose-pen: space allowance. Space allowance may have influenced the variety of lying postures utilized by the cows when lying down, facilitating alternative resting postures in LP cows. For example, LP cows in the current study tended to position their heads towards their back in a full resting posture more than TS cows, concurring with previous studies in both loose-pen housing (5.3 % vs. 4.8 %, loose-pen vs. tie-stall, respectively; Haley *et al*, 2000) and in cows housed in double-width stalls (8.1 % vs. 7.2 %, double-width vs. standard-width stall, respectively; Boyer *et al*, 2018). The posturing of the head

to rest toward the back has been associated with the occurrence of rapid eye motion in dairy cows (Ternman *et al*, 2014), signifying this position to be indicative of deep sleep in the animal.

Likewise, more space may have increased the ease with which the cow moved between different leg postures, resulting in higher displays of partial and full extension of the legs in LP cows. Offering stalls that were doubled in width from a standard-sized stall (2.8 m vs. 1.4 m) was found to similarly increase the occurrences of hind leg extension when lying (Boyer *et al.*, 2018). Furthermore, it is also possible that, while tie-stall cows do still exhibit mid-position and extended posturing of their legs, this is at the expense of the space and potential comfort of the neighboring cow. Cows in tie-stalls were observed with their hind legs in the neighboring stall more than 20 % of the total observed time in the current study. This is comparable to Boyer *et al.*(2018) that documented hind legs of single-stall cows in the neighboring stall 14.7 % of observed time, but only 1.3 % of the time in cows provided a double-width stall. More space provides cows with the ability to fully extend the hind legs without encroaching on the stall space of the neighboring cow. This may have implications for the cow as disturbances during lying may negatively affect comfort as well as lying time.

A final feature that most often differs between stall-based housing and systems such as our loose-pens that use deep-bedded packs is the lying surface. While not significant, lying time was 1.5 h/d higher in loose-pen housed dairy cows in the current study, which agrees with previous findings for deep-bedded strawyard-housed dairy cows when compared to cubicle housing (Fregonesi and Leaver, 2001). Tucker *et al.*(2009) found that increased depth and more compressible bedding types positively impacted lying time, with differences in lying time up to 1.4 h/d between stalls bedded with 3 kg of wood shavings (compressibility = 1.9 cm) vs. just 7 kg of straw (compressibility = 14.6 cm). However, this difference could also be attributed to normal

variation in lying time found amongst individual cows, warranting further investigation. Lying-down ability may, likewise, benefit from a more compressible and comfortable lying surface, as seen by the numerically lower time to lie down found in LP cows in our study. This concurs with previous findings by Krohn and Munksgaard (1993) where strawyard-housed cows with pasture access took less time and fewer attempts to lie down than their tie-stall counterparts. Harder lying surfaces can lead to higher incidences of swelling of the carpal joints (Rushen *et al*, 2007), which may increase the cow's discomfort during the beginning stages of lying when she drops to her knees as she is placing a great deal of force on the carpal joints. Deeper bedding or more compressible lying surfaces may absorb some of this force and, thus, increase the ease with which the cow carries out her lying-down behaviours. The compressibility of the LP lying surface was slightly better than that of the stall, suggesting that, while there may have been an increased cushioning effect, compressibility in combination with other aspects of the cow's lying surface may have led to the increased lying time and lying-down ease for LP cows in our study.

4.6 CONCLUSION

Housing tie-stall dairy cows in a deep-bedded loose-pen during the 8-wk dry period proved to be beneficial to overall lying time, lying and rising ability, and lying posture display. This includes greater ease of movement when transitioning between standing and lying, an increase in ability to assume different lying postures that may maximize cow comfort, and numeric increases in total lying time. These benefits can be attributed to a combination of fewer obstacles in the cow's environment, increased space for the cow's lying area, and the provision of a more comfortable lying surface. Many of the results of our study are associated with aspects of the stall itself – a characteristic of both tie-stall and free-stall housing systems – warranting further research

to determine if cows in free-stall systems may also benefit from loose-pen-housing during the dry period.

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Supplementary Table S4.1. Variances parameters (σ^2_{cow} , σ^2_{e} , CS), phenotypic variance (σ^2_{p})¹, variable mean ($\bar{x}$)², and coefficient of variation (CV)³ between tie-stall (TS) and loose-pen (LP) treatments.

Variable	σ^2_{cow}	AR(1)	CS	σ^2_{e}	σ^2_{p}	$\bar{x}$	CV (%)
Lying Time	0.00	0.82	-	3.61	3.61	13.71	13.86
Lying-down Behaviours							
Intention Time	0.00	0.35	-	80.48	80.48	22.22	40.37
Time to Lie Down	-	-	2.88	2.37	5.25	6.08	37.69
Contact	353.39	-0.76	-	291.07	644.46	29.76	94.87
Attempts to lie down	0.00	0.32	-	0.00	0.00	1.00	0.00
Hind quarter shifting	-	-	391.89	253.57	645.46	16.40	154.91
Dog-sitting	-	-	-	-	-	-	-
Side, left	-	-	269.13	416.66	685.79	46.57	56.23
Side, right	-	-	269.13	416.66	685.79	53.43	49.01
Overall abnormal lying	542.65	-0.59	-	251.63	794.28	44.22	63.73
Rising Behaviours							
Time to rise	8.95	-0.53	-	1.83	10.78	7.70	42.64
Contact	-	-	305.03	125.39	430.42	11.64	178.24
Backward on knees	115.78	-0.59	-	202.69	318.47	12.61	141.52
Delayed Rising	-	-	215.58	43.30	258.88	3.41	471.84
Rising attempts	0.00	0.87	-	0.71	0.71	1.53	55.07
Horse rising	-	-	-	-	-	-	-
Overall abnormal rising	-	-	700.52	400.92	1101.44	45.28	73.29

¹ σ^2_{p} = the sum of all applicable variance parameters

² $\bar{x}$ = the average between the TS and LP treatment means

³CV = $\sqrt{\sigma^2_{\text{p}}}/\bar{x}$

Supplementary Table S4.1. Continued.

Variable	σ^2_{cow}	AR(1)	CS	σ^2_e	σ^2_p	$\bar{x}$	CV (%)
Lying Postures							
Side, right	-	-	149.87	132.16	282.03	48.76	34.44
Side, left	-	-	149.44	133.51	282.95	51.09	32.92
Body, Sternum	-	-	2.01	1.39	3.40	99.04	1.86
Body, Side	-	-	2.18	0.83	3.01	0.80	216.87
Head, upright	0.00	-0.93	-	4.33	4.33	91.91	2.26
Head, back	-	-	0.95	5.37	6.32	7.35	34.20
Head, ground	-	-	0.85	0.41	1.26	0.56	200.45
Front leg, tucked	-	-	30.73	16.32	47.05	92.56	7.41
Front leg, extended	-	-	31.21	14.98	46.19	7.27	93.48
Hind leg, tucked	-	-	22.97	21.52	45.49	79.53	8.48
Hind leg, extended	-	-	25.71	5.61	31.32	7.42	75.42
Hind leg, mid-position	-	-	33.14	12.32	45.46	12.88	52.35

Supplementary Table S4.2. Mean $\pm$ SEM, variance, and coefficient of variation (CV) ¹ for all measured study variables.

Variable	Mean $\pm$ SEM	σ	CV ¹
Lying Time	13.76 $\pm$ 0.26	3.29	0.24
Lying-down Behaviours			
Intention Time	21.92 $\pm$ 1.43	104.63	0.21
Time to Lie Down	6.08 $\pm$ 0.27	3.63	0.60
Contact	29.31 $\pm$ 4.34	960.65	32.77
Attempts to lie down	1.00 $\pm$ 0.00	0.00	0.00
Hind quarter shifting	14.44 $\pm$ 3.59	656.31	45.45
Dog-sitting	-	-	-
Side, left	47.91 $\pm$ 3.05	472.56	9.86
Side, right	52.09 $\pm$ 3.05	472.56	9.07
Overall abnormal lying	41.47 $\pm$ 4.77	1162.50	28.02
Rising Behaviours			
Time to rise	7.65 $\pm$ 0.46	10.95	1.43
Contact	12.84 $\pm$ 2.51	320.03	24.92
Backward on knees	11.21 $\pm$ 2.55	332.34	29.65
Delayed Rising	3.59 $\pm$ 2.00	203.48	56.68
Rising attempts	1.52 $\pm$ 0.12	0.71	0.47
Horse rising	-	-	-
Overall abnormal rising	45.26 $\pm$ 4.54	1050.37	23.21
Lying Postures			
Side, right	48.21 $\pm$ 1.77	159.28	3.30
Side, left	51.70 $\pm$ 1.78	161.57	3.13
Body, Sternum	99.14 $\pm$ 0.28	4.10	0.04
Body, Side	0.76 $\pm$ 0.27	3.80	5.00

¹CV = $\sigma / \bar{x}$

Supplementary Table S4.2. Continued.

Variable	Mean $\pm$ SEM	σ	CV ¹
Lying Postures			
Head, upright	91.84 $\pm$ 0.40	8.30	0.09
Head, back	7.48 $\pm$ 0.47	11.38	1.52
Head, ground	0.54 $\pm$ 0.15	1.14	2.11
Front leg, tucked	92.57 $\pm$ 0.88	39.68	0.43
Front leg, extended	7.33 $\pm$ 0.89	40.09	5.47
Hind leg, tucked	79.79 $\pm$ 1.89	182.53	2.29
Hind leg, extended	7.95 $\pm$ 0.85	36.50	4.59
Hind leg, mid-position	12.16 $\pm$ 1.52	117.08	9.63
Locations, tie-stall			
Head, divider	9.34 $\pm$ 2.70	174.52	18.69
Head, manger	69.66 $\pm$ 6.27	942.73	13.53
Head, stall	20.71 $\pm$ 6.28	945.03	45.63
Head, neighbor's stall	0.08 $\pm$ 0.04	0.03	0.38
Front leg, manger	4.07 $\pm$ 1.10	29.18	7.17
Front leg, stall	95.47 $\pm$ 1.13	30.45	0.32
Front leg, neighbor's stall	0.25 $\pm$ 0.08	0.17	0.68
Hind leg, stall	75.98 $\pm$ 2.18	113.69	1.50
Hind leg, neighbor's stall	21.69 $\pm$ 2.06	101.85	4.70
Hind leg, alleyway	2.12 $\pm$ 0.82	16.28	7.68
Locations, loose-pen			
Time in Quadrant	31.50 $\pm$ 3.48	874.35	27.76

¹CV = $\sigma / \bar{x}$

Supplementary Table S4.3. LSMEAN $\pm$ SEM for tie-stall (TS) and loose-pen (LP) treatments, differences between treatment least square means, denominator degrees of freedom for treatment, and p-value denoting significance between treatments for all analyzed variables.

Variable	TS, LSMEAN $\pm$ SEM	LP, LSMEAN $\pm$ SEM	Difference	Ddf	F- Value	P- value
Lying Time	13.02 $\pm$ 0.67	14.40 $\pm$ 0.61	1.46 $\pm$ 0.92	5.95	2.22	0.19
Lying-down Behaviours						
Intention Time (s)	19.70 $\pm$ 1.50	24.79 $\pm$ 1.36	5.09 $\pm$ 2.06	10.00	6.13	0.03
Time to Lie Down (s)	6.56 $\pm$ 0.75	5.60 $\pm$ 0.67	-0.95 $\pm$ 1.02	6.00	0.86	0.39
Contact (%)	49.87 $\pm$ 7.65	9.64 $\pm$ 6.90	-40.23 $\pm$ 10.51	6.47	4.66	< 0.01
Attempts to lie down (no. of attempts)	1.01 $\pm$ 0.01	1.00 $\pm$ 0.01	-0.01 $\pm$ 0.01	4.90	0.79	0.42
Hind quarter shifting (%)	24.25 $\pm$ 8.49	8.54 $\pm$ 7.65	-15.71 $\pm$ 11.67	6.00	1.81	0.23
Dog-sitting (%)	-	-	-	-	-	-
Side, left (%)	42.56 $\pm$ 7.86	50.58 $\pm$ 7.08	-8.02 $\pm$ 10.80	6.00	0.55	0.49
Side, right (%)	57.44 $\pm$ 7.86	49.42 $\pm$ 7.08	8.02 $\pm$ 10.80	6.00	0.55	0.49
Overall abnormal lying (%)	70.30 $\pm$ 9.35	18.14 $\pm$ 8.43	-52.16 $\pm$ 12.85	6.15	16.49	< 0.01
Rising Behaviours						
Time to rise (s)	9.17 $\pm$ 1.18	6.23 $\pm$ 1.06	-2.95 $\pm$ 1.62	6.06	3.29	0.12
Contact (%)	10.02 $\pm$ 7.25	13.27 $\pm$ 6.53	3.25 $\pm$ 9.95	6.00	0.11	0.75
Backward on knees (%)	17.05 $\pm$ 4.67	8.16 $\pm$ 4.21	-8.89 $\pm$ 6.41	6.51	1.92	0.21
Delayed Rising (%)	6.98 $\pm$ 5.90	-0.16 $\pm$ 5.32	-7.14 $\pm$ 8.11	6.00	0.78	0.41

Variable	TS, LSMEAN ± SEM	LP, LSMEAN ± SEM	Difference	Ddf	F- Value	P- value
Rising Behaviours						
Rising attempts (no. of attempts)	1.81 ± 0.30	1.24 ± 0.27	-0.56 ± 0.42	6.45	1.82	0.22
Horse rising (%)	-	-	-	-	-	-
Overall abnormal rising (%)	50.83 ± 11.24	39.72 ± 10.12	-11.11 ± 15.44	6.00	0.52	0.50
Lying Postures						
Side, right (%)	48.82 ± 5.42	48.71 ± 4.88	-0.11 ± 7.44	6.00	0.00	0.99
Side, left (%)	51.03 ± 5.42	51.14 ± 4.88	0.11 ± 7.44	6.00	0.00	0.99
Body, Sternum (%)	99.45 ± 0.61	98.63 ± 0.55	-0.82 ± 0.84	6.00	0.96	0.36
Body, Side (%)	0.38 ± 0.61	1.21 ± 0.55	0.83 ± 0.84	6.00	0.98	0.36
Head, upright (%)	92.56 ± 0.35	91.27 ± 0.32	-1.29 ± 0.48	17.3	7.20	0.02
Head, back (%)	6.38 ± 0.64	8.32 ± 0.58	1.94 ± 0.89	6.00	4.78	0.07
Head, ground (%)	0.93 ± 0.39	0.20 ± 0.35	-0.74 ± 0.53	6.00	1.91	0.22
Front leg, tucked (%)	95.02 ± 2.34	90.09 ± 2.11	-4.93 ± 3.21	6.00	2.35	0.18
Front leg, extended (%)	4.80 ± 2.34	9.74 ± 2.11	4.94 ± 3.22	6.00	2.36	0.18
Hind leg, tucked (%)	89.29 ± 2.14	69.77 ± 1.92	-19.52 ± 2.93	6.00	44.23	< 0.001
Hind leg, extended (%)	3.75 ± 2.04	11.09 ± 1.84	7.35 ± 2.81	6.00	6.85	< 0.001
Hind leg, mid- position (%)	6.80 ± 2.38	18.97 ± 2.14	12.18 ± 3.26	6.00	13.93	< 0.01

Supplementary Table S4.3. Continued.

Supplementary Table S4.4. Lying-down and rising behaviours for tie-stall (TS) and loose-pen (LP) treatments, presented as mean $\pm$ S.E., during the early, mid, and late term of the dry period.

		Term		
Behavior	Treatment	Early	Mid	Late
Lying-down				
Intention Time (s)	TS	19.50 ± 1.64	20.66 ± 1.41	26.59 ± 2.56
	LP	20.05 ± 2.25	23.61 ± 1.93	30.72 ± 3.51
Time to Lie Down (s)	TS	6.52 ± 1.00	6.27 ± 1.00	6.77 ± 1.00
	LP	5.21 ± 0.91	5.1 ± 0.91	6.44 ± 11.72
Attempts to Lie Down (no. of occurrences)	TS	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00
	LP	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00
Hind Stepping (%)	TS	16.94 ± 10.77	14.86 ± 10.77	†41.94 ± 10.77
	LP	10.62 ± 9.79	8.38 ± 9.79	†11.72 ± 9.79
Contact (%)	TS	46.19 ± 9.81	47.23 ± 9.81	56.61 ± 9.81
	LP	11.58 ± 8.99	10.1 ± 8.99	7.87 ± 8.99
Overall Abnormal Lying (%)	TS	62.43 ± 10.33	65.55 ± 10.33	81.18 ± 10.33
	LP	16.84 ± 9.44	19.44 ± 9.44	18.7 ± 9.44
Rising				
Time to Rise (s)	TS	9.07 ± 1.28	8.57 ± 1.28	9.94 ± 1.28
	LP	5.68 ± 1.16	6.24 ± 1.16	6.79 ± 1.16
Contact (%)	TS	7.24 ± 7.94	^a 5.15 ± 7.94	^b 17.65 ± 7.94
	LP	14.44 ± 7.20	17.22 ± 7.20	8.15 ± 7.20
Delayed Rising (%)	TS	6.24 ± 6.90	4.16 ± 6.90	10.41 ± 6.90
	LP	0.00 ± 0.00	0.00 ± 0.00	1.85 ± 1.75
Rising Attempts (no. of occurrences)	TS	1.73 ± 0.33	1.77 ± 0.33	1.87 ± 0.33
	LP	1.46 ± 0.30	1.52 ± 0.30	1.57 ± 0.30
Backward on Knees (%)	TS	17.95 ± 7.02	11.70 ± 7.02	22.12 ± 7.02
	LP	9.81 ± 6.46	5.18 ± 6.46	8.14 ± 6.46
Overall Abnormal Rising (%)	TS	49.1 ± 12.64	48.06 ± 12.64	55.35 ± 12.64
	LP	36.7 ± 11.50	39.66 ± 11.50	42.81 ± 11.50

[†] Denotes tendency at a p-value < 0.10

^{a,b} Differences in superscripts denotes significance at a p-value < 0.05

CHAPTER 5 — THE EFFECT OF HOUSING TIE-STALL DAIRY COWS IN DEEP-BEDDED PENS DURING AN EIGHT-WEEK DRY PERIOD ON GAIT AND COW LOCOMOTOR ACTIVITY

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5.1 ABSTRACT

Increasing locomotor activity can improve leg health and decrease the prevalence of lameness in dairy cows. The dry period offers an opportunity to provide alternative housing to tie-stall cow that can increase locomotor activity. The objective was to determine if housing tie-stall dairy cows in a deep-bedded loose pen during the 8-week dry period affected gait and step activity. Twenty cows, paired by parity and calving date, were assigned at dry-off to a deep-bedded loose-pen (LP) or a tie-stall (TS). Step activity was measured by leg-mounted pedometers. Cows were walked 1x/wk on a test corridor and video recordings of gait were taken. Six aspects of gait were scored on a 0-5 scale (interval: 0.1): tracking up, joint flexion, back arch, asymmetric step, swing, and reluctance to bear weight. Overall gait was also scored using a 1-5 scale (interval: 0.5). Data for gait were analyzed based on the change in gait between the dry-off and calving. Daily step data was averaged per week of the dry period. Analyses were performed using a using a mixed model with treatment, week, and pair as fixed effects and cow nested within pair as a random effect for step data. The same model, omitting the fixed effect of week, was used for gait. There was no difference in step activity between LP and TS cows (842.1 ± 88.86 vs. 799.5 ± 76.92 steps/d, LP vs. TS, respectively; $P = 0.73$). Only joint flexion yielded a treatment difference with LP cows improving over time and TS cows worsening (-0.4 ± 0.15 vs. $+0.2 \pm 0.16$; $P < 0.05$). Although step activity was similar in both housing options, the increased space allowance in the LP treatment

may have allowed for a larger range of motion for each steps, increasing the overall benefits to leg health. The denser lying surface in the LP may also have provided a cushioning effect when transitioning between rising and lying, improving joint health and, thus, joint flexion. Providing tie-stall cows with alternative housing during the dry period has the potential to help cows to recover in preparation for their next lactation.

Keywords: Dry Cow, Gait, Housing, Lameness

5.2 INTRODUCTION

Tie-stall housing of dairy cows, a common system found in Canada (74 %; CDIC 2018) and the United States (39 %, tie-stall and stanchion; USDA-APHIS, 2014), is characterized by its restriction of the cow's ability to move. This restriction of movement is of particular concern, with a recent survey showing that the more time per day that a cow is kept tied at her stall, the more critical of the housing system the public becomes (Robbins *et al.*, 2019). Conversely, dairy housing systems that provide outdoor access or pasture not only fit the mental image of an ideal dairy farm for consumers (Cardoso *et al.*, 2016), but are also linked with benefits to the cow such as improved leg health and decreased lameness prevalence (Regula *et al.*, 2004; Popescu *et al.*, 2013). While the causes behind the reported leg disorders may be multifactorial, they are particularly exacerbated when the cows are raised in an indoor confinement system (Haskell *et al.*, 2006).

While changing housing systems at the herd level cannot be done easily or quickly, the provision of outdoor access may be a more applicable and affordable option which has also been found to improve lameness and injury of cows in both tie-stall and free-stall housing systems (Regula *et al.*, 2004). The increase in movement opportunity and overall activity in the less restrictive outdoor environments may, even if applied for a short period of time, help counterbalance the effects of these indoor, stall-based systems, particularly with regard to leg

health (Hernandez-Mendo *et al.*, 2007). A more selective option to providing alternative housing to an entire herd is to utilize periods of the animal's life during which time she is already managed differently than the rest of the herd (e.g., not lactating), such as the dry period. This offers cows a period of respite from her existing housing and places her into a housing environment that is more conducive to comfort and ease of movement. The objective of this study was to determine if housing tie-stall Holstein dairy cows in deep-bedded loose-pens vs. a tie-stall during an 8-wk dry period improved aspects of gait and lameness score. We also sought to determine if the loose-pen housing was associated with increases in locomotor activity, measured through average daily number of steps taken by the cow.

5.3 MATERIALS AND METHODS

This study was part of a larger study aimed at evaluating the impact of housing dairy cows in deep-bedded loose-pens which included the analysis of the housing system's impact on lying time and lying behaviours (Shepley *et al.*, 2019). The study was conducted at the Macdonald Campus Dairy Unit of McGill University (Sainte-Anne-de-Bellevue, Quebec, Canada). A certified Animal Care Committee of McGill University reviewed and approved the use of animals in this project and all procedures (#2016-7794). All aspects of this study meet the standards established by the Canadian Council on Animal Care (Ottawa, Ontario) to ensure the continued humane and ethical use of animals in research.

5.3.1 Animals and Treatments

Twenty Holstein cows were enrolled between August 2016 and March 2018 at dry-off, with cows blocked based on expected calving date and parity (mean $\pm$ SD = 2.1 $\pm$ 1.00 and 2.6 $\pm$ 1.42; range = 1-4 and 1-6; tie-stall and loose-pen, respectively). Three cows were removed from the analysis due to reasons unrelated to the treatment: one due to aborting her calf at the start of

the dry period, one that was dried off prematurely, and a third due to poor temperament that hindered safe handling of the cow. Thus, a total of nine cows in the loose-pen treatment and eight cows in the tie-stall treatment were used in the analysis. Each pair of cows was randomly allocated to one of the two treatment options: loose-pen (LP) or tie-stall (TS). Gait score of cows at the start of the study (mean $\pm$ SD) was 2.3 ± 0.43 (range: 2.0 – 3.0) and 2.6 ± 0.46 (range: 1.5 – 3.0) for TS and LP, respectively, measured on a 1 – 5 NRS scale where ≥ 3 indicates lameness. Body condition scores (BCS) at the beginning and end of the trial, respectively, were 2.6 ± 0.25 and 2.7 ± 0.21 (mean $\pm$ SD, loose-pen) and 2.8 ± 0.34 and 2.9 ± 0.38 (tie-stall).

The start date for each pair was staggered over the course of the study from September 2016 to December 2017. Cows were dried off and enrolled eight weeks before their expected calving date; however, the mean amount of time between dry-off and calving for this study was 8.34 weeks for tie-stall (range: 7.29 – 9.86) and 7.51 weeks for loose-pen (range: 6.57 – 8.71). Cows in the LP treatment calved in their experimental pens. Cows in the TS treatment were moved to a calving pen when physical signs of imminent calving were observed by barn staff (mean 3.63 d before calving, range 0-12 d). Physical signs included rapid filling of the udder, mucosal discharge and/or swelling of the vulva, and changes in behaviours (e.g., restlessness, decreased appetite). After calving, both LP and TS cows were moved back to a tie-stall housing system.

5.3.2 Housing and Management

All cows were previously housed in tie-stalls during their lactation. The deep-bedded loose-pen housing was comprised of four individual pens measuring 3.35 m x 4.88 m (16.35 m² total) each. Pens were bedded with straw to 20.0 cm in depth on a base of concrete topped with 1.9 cm thick rubber mats (Ani-Mats, Ani-mat Inc., Sherbrooke, QC, Canada). A thin layer of lime was applied onto of the rubber mats before bedding was placed. Each pen had a 38.4 cm H x 76.5 cm

W x 60.96 D feed bin (Stack-N-Nest, LewisBins+, Oconomowoc, WI, USA) and a water bowl. The tie-stall housing consisted of stalls measuring 1.41 m W x 1.87 m H. Stalls were bedded with 2.0 cm of wood shavings on a 4.4 cm pasture mat base (KKM longline; Distribution Multi-Mat, Inc. Ste-Cécile-de-Milton, QC, Canada). A single water bowl was shared between every two stalls. Both the loose-pen and tie-stall housing systems were designed to either meet or exceed current recommendations set by the Dairy Code of Practice (Dairy Farmers of Canada-National Farm Animal Care Council, 2009). Compressibility of the lying surface for both treatments was measured once during the trial using a 10 kg Clegg hammer (Clegg impact soil tester; Lafayette Instrument Company, Lafayette, IN, USA). The average compressibility of the stall base with 2.0 cm of bedding was 5.18 CIV/H (Clegg impact value/heavy hammer) and average compressibility of the deep-bedded loose-pens was 4.85 CIV/H. Lower values denote a higher compressibility.

Tie-stalls were cleaned frequently as per routine management with any contaminants removed when seen by passing barn staff (avg. 15 passes/d). Fresh wood shavings were added daily to maintain 2.0 cm of bedding throughout the course of the study. Loose-pens were cleaned once in the morning with fresh bedding added to maintain a 20.0 cm depth of bedding. Pens were also spot-cleaned once daily in the evening to remove any visible manure. All cows were fed two different rations during the course of the study: a far-off (dry-off until week 5) and a close-up TMR (week 6 until calving). An average of 21.1 kg/d of far-off TMR was fed from the start of dry-off to three weeks prior to expected calving and was comprised of 48.0 % hay, 46.7 % silage, 4.3 % protein supplement, and 1.0 % vitamin and mineral supplement. An average of 24.6 kg/d of close-up TMR was fed from three weeks prior to expected calving to the date of actual calving and was comprised of 17.2 % hay, 69.0 % silage, 9.0 % protein supplement, 4.4 % energy supplement, and

0.4 % vitamin and mineral supplement. Rations were fed once in the morning at approximately 07:00 h. Hay was fed ad libitum to cows during the dry period.

5.3.3 Test Corridor for Gait Evaluation

Based on the design presented by Franco-Gendron *et al.* (2016), a test track containing a straight test corridor measuring 1.8 m wide by 8.1 m long was created in a designated experimental area to test ease of movement (Figure 5.1). On each side of the straight test corridor, three high-speed cameras (120 fps, 720 resolution; GoPro Hero 4, GoPro, Inc., San Mateo, California, USA), positioned on a tripod, were placed at a distance of 2.4 m from the center of the test corridor.

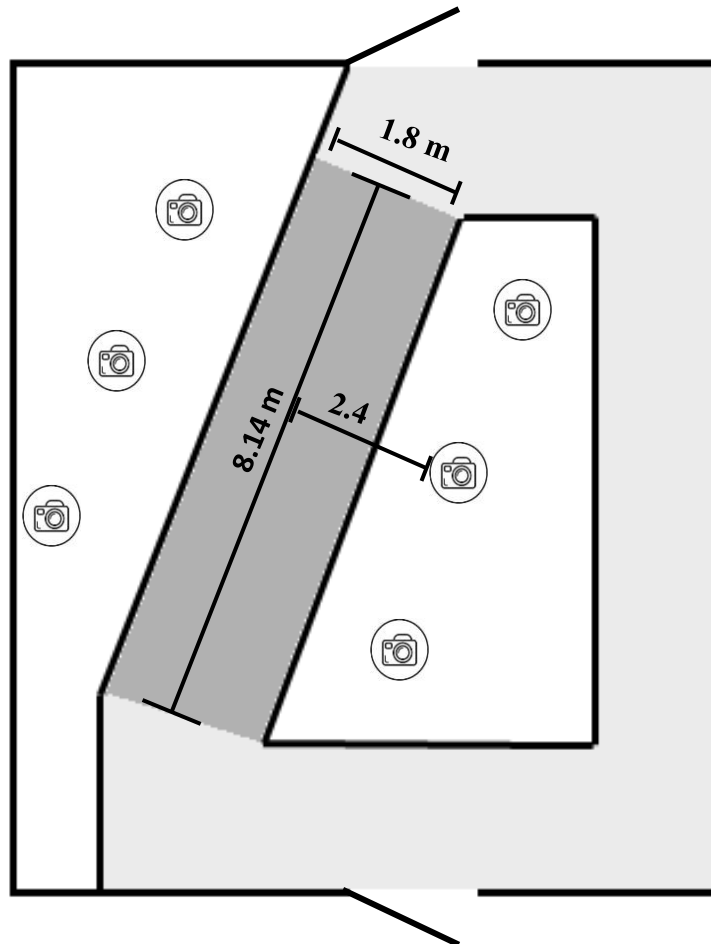


Figure 5.1. Layout of the experimental area with the walking circuit indicated in light grey and the test corridor in dark gray. Placement of the six cameras indicated in circles.

The flooring used for the test corridors were rubber mats (Ani-Mats, Ani-mat Inc., Sherbrooke, QC, Canada) measuring 1.2 m in width by 1.8 m in length. The rubber mats in the test corridor were completely covered with shavings to reduce hesitation in the cows while walking on in the corridor and to facilitate the cleaning of any excrement to maintain clean, dry floors at all times to reduce the risk of slipping. Corridors were outlined with highly visible nylon rope supported by posts fixed into sand-filled buckets.

5.3.4 Training and Gait Recording

Two weeks prior to dry-off and enrollment in the study, cows were taken out of their stalls twice per week and brought to the experimental area. Cows were individually walked for multiple circuits during each training session on the test corridor to allow for habituation to the test area and procedures. This habituation period was to ensure that scores for ease of movement measurements were a reflection of the cow's locomotive abilities and not due to the novelty of the area and or task being required of the cows. Any cows that showed indications of poor habituation to the test methodology or displayed any health issues that might impact other measures recorded were excluded from the study.

Upon enrollment in the study, cows were taken to the experimental area once per week until calving to record the cow's gait. Cows were walked in the same method described in Franco-Gendron *et al.* (2016), described here briefly; however, as experience walking was minimal for cows enrolled in the current study, cows were led with a halter by a handler during the course of the test process. Cows were walked for at least five passages on the straight test corridor, ensuring that at least one passage in which the cow was walking at a consistent pace without stopping was captured. If needed, a handler with a bucket of grain walked approximately 1.0 m in front of the cow to entice her to move forward while a second handler followed behind at and slightly to the

side of the cow at the cow's point of balance. All passages were simultaneously recorded by the six high-speed cameras to capture video recordings of the cow's gait using a remote starter (GoPro Smart Remote Control, GoPro, Inc., San Mateo, California, USA).

5.3.5 Measures

Visual gait analysis

From the available passages for each cow, the gait passage in which the cow was walking at the most consistent speed without stopping was selected. Six gait behaviours were scored by two trained observers: swinging out, back arch, tracking-up, joint flexion, asymmetric gait, and reluctance to bear weight (Table 5.1). Scores were assigned on a 0-5 scale with 0.1 intervals. An overall gait score was also assigned to each cow based on the 1 to 5 numeric rating scale (NRS) outlined in Flower and Weary (2006; Table 5.2). Inter-observer reliability had a weighted kappa (K_w) = 0.87 (range: 0.78 - 0.94) while intra-observer reliability K_w = 0.97 (range: 0.90 - 1.00). Gait was analyzed for the early (first week of dry-off), mid, and late (last week before calving) terms of the dry period.

Step Activity

Step activity was recorded continuously throughout the course of the dry period using a 3D pedometer (IceTag™, IceRobotics, Edinburgh, Scotland) attached on the rear leg of the cow. Pedometer data was retrieved weekly. The pedometers used were validated previously for use in both loose-housing systems (Higginson *et al.*, 2010) and tie-stall systems (Shepley *et al.*, 2017). Data was output in one-minute intervals that were summed per day and sum of each day was then averaged by week. Step activity times were analyzed for the early (first week of dry-off), mid, and late (last week before calving) terms of the dry period.

Table 5.1. Description of visual gait variables and the corresponding endpoints of a visual analogue scale where 0 indicates the best possible visual appearance for a gait variable and 100 is the worst; adapted from Flower and Weary (2006).

Gait Measure	Definition	Endpoint of Visual Analogue Scale	
		0	5
Swinging out	The degree to which the hind leg moves side to side when walking	Hind legs moving in straight line during the swing phase	Pronounced, circular motion of the hind legs during the swing phase
Arch back	The shape of the spine when the cattle walks	Flat spine	Convex arch between the withers and tailbone
Tracking up	It is the gap between the imprint left behind the front hoof and the new imprint formed from the rear hoof	Hind hoof falls in imprint left by the front hoof of the same side	Hind hoof falls short of the imprint left by the front hoof of the same side
Joint flexion	Related to the flexes and extensions of the limb while the cow is moving	All limbs flex and extend easily	All limbs are stiff and limited in their range of motion
Asymmetric step	How even the stepping pattern of a cow is	Equal steps; cow places her hooves in an even “1, 2, 3, 4” rhythm	Not equal; cow places her hooves in an uneven rhythm
Reluctance to bear weight	How evenly the cow distributes her weight when walking	Bears weight equally over all legs	Uneven weight bearing between legs

Table 5.2. Lameness category, description, and associate behaviours for the numerical rating scores (NRS) for dairy cattle gait (scores range from 1 to 5), based on Flower and Weary (2006).

Score	Category2	Description1	Associated behaviours1
1.0	Normal/Sound	Smooth and fluid movement	- Flat back - Hind hooves track up with front hooves - Joints flex freely - Symmetrical gait - All legs bear weight equally
2.0	Mildly lame	Imperfect locomotion but ability to move freely not diminished	- Flat or mildly arched back - Hind hooves do not track up perfectly - Joints slightly stiff - Slightly asymmetric gait - All legs bear weight equally
3.0	Moderately lame	Capable of locomotion but ability to move freely is compromised	- Arched back - Hind hooves do not track-up - Joints show signs of stiffness - Asymmetric gait - Slight limp can be discerned
4.0	Lame	Ability to move freely is obviously diminished	- Obvious arched back - Hind hooves do not track-up - Joints are stiff and strides are hesitant - Asymmetric gait - Reluctant to bear weight on at least one limb; still uses that limb in locomotion
5.0	Severely lame	Ability to move is severely restricted and must be vigorously encouraged to move	- Extremely arched back - Poor tracking-up with short strides - Obvious joint stiffness with a lack of joint flexion; very hesitant, deliberate strides - Asymmetric gait - Inability to bear weight on one or more limbs

5.3.6. Statistical analysis

All analyses were run in a statistical analysis software, SAS 9.4 (SAS Institute, 2008) and were conducted at the cow level using a mixed model procedure (PROC MIXED and LSMEANS), following the model:

$$\gamma_{ijkm} = \mu + \text{Treatment}_i + \text{Block}_j + \text{Cow}_{jk} + \text{Week}_m + \text{Treatment}_i \times \text{Week}_m + e_{ijkm}$$

where γ_{ijkm} represents the observation, μ is the population mean, treatment_i is the fixed effect of the i^{th} treatment (TS, LP), block_j is the fixed effect of the j^{th} block (1-10), cow_{jk} is the random effect of the k^{th} cow in the j^{th} block (1-2), week_m is the fixed effect of the m^{th} week (1-9), and e_{ijkm} represents the residual error. Repeated measures for week were analyzed using two relevant covariance structures: compound symmetry and autoregressive lag 1 (Supplementary Table S5.1). Scheffé's adjustment was used to account for multiple comparisons in the analysis of term and the interaction between treatment and term. Normality was tested against the residuals for all variables using the PROC UNIVARIATE and PROC MIXED procedures. A Spearman Rank correlation was carried out to determine the correlation between level of step activity and change in gait variable scores.

5.4. RESULTS AND DISCUSSION

In the current study, step activity showed no difference between LP and TS treatments (818.8 ± 75.46 vs. 748.5 ± 75.59 steps/d, respectively; denominator degrees of freedom (ddf) = 6.03, F-value = 0.38, P = 0.56; Supplementary Table S5.3), suggesting no difference in the activity levels of the two treatments. Surface area has been shown to have a significant impact on locomotor activity in free-stall housed cows (Telezhenko *et al.*, 2012). This is evident when comparing step activity recorded in indoor housing systems (free-stall: 1,121-1,520 steps/d; Brzozowska *et al.*, 2014, Dohme-Meier *et al.*, 2014, Shepley *et al.*, 2018; bedded packs: 1,044-

1,485, Eckelkamp *et al.*, 2014, Shepley *et al.*, 2018) to housing that provides more space through outdoor access (1,989-2,374 steps/d, Eckelkamp *et al.*, 2014, Borchers *et al.*, 2017; 4,064 steps/d in pasture-based housing, Dohme-Meier *et al.*, 2014). The pens in the current study were not designed as exercise yards and thus may have lacked the amount of surface area necessary to elicit a substantial increase in movement in the LP cows when compared to other housing options.

Moreover, the LP treatment, much like any other loose-housing system, offers the cow with more movement opportunity, but does not force the cow to move. There was a tendency for cows, independent of treatment, that ranked as having a higher number average daily steps to also be ranked as having a greater improvement in swinging out ($r = 0.43$, $P = 0.08$), tracking up ($r = 0.43$, $P = 0.09$), joint flexion ($r = 0.45$, $P = 0.07$), and overall gait score ($r = 0.42$, $P = 0.09$; Figure 5.2). Individual cows show considerable differences in their motivation to perform locomotor activity (Alsaad *et al.*, 2012) and these activity levels have been found to have long-term consistency across time (Müller and Schrader, 2005). As such, it is possible that cows in the LP housing that were less inclined to display higher levels of step activity may not have increased their level of step activity when released from their stalls into the LP treatment. Releasing the cow from her stall may be a possible option to increase locomotor activity in more active cows, however, alternative methods may be required for animals less inclined to move if attenuation of the same benefits on cow health are desired.

Despite a lack of difference in step activity between the treatment groups, cows in the LP treatment showed significant improvement in joint flexion between the early and late terms of the dry period (-0.43 ± 0.147 vs. 0.23 ± 0.163 , LP vs. TS, respectively, $P < 0.05$; Table 5.3). One explanation for these seemingly diametric results between step activity and gait is that the quality of the steps taken by the cow in each housing environment. LP housing may have allowed for

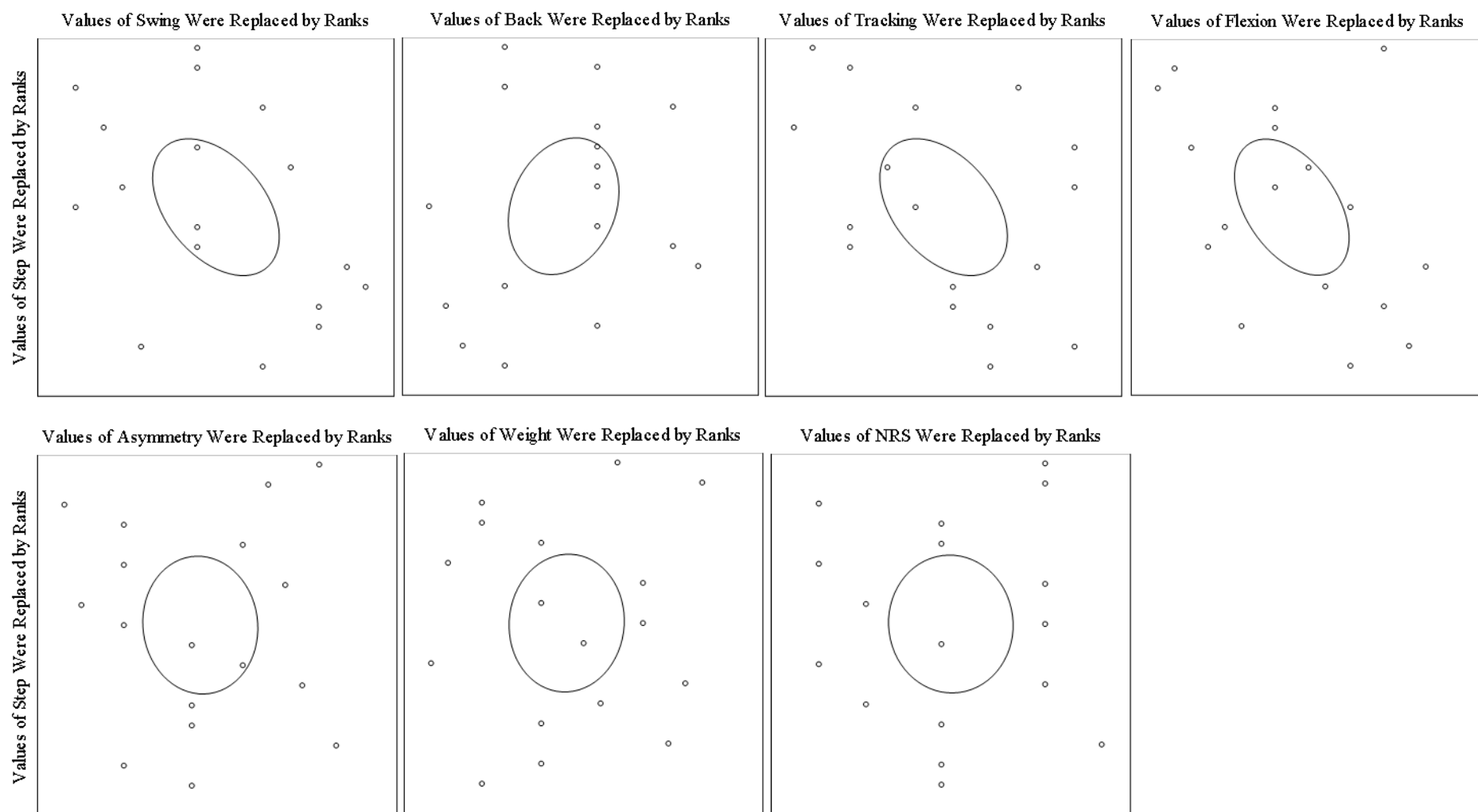


Figure 5.2. Scatterplot for the Spearman rank correlations between step activity (avg. steps/d) and variables of gait (Swinging out, back arch, tracking up, joint flexion, asymmetric step, and reluctance to bear weight) and overall NRS gait score.

Table 5.3. Gait variables, reflecting the change in gait score between the early (first week of dry off) and late (last week before calving), and step activity (average steps/d across the dry period) when housed in a Tie-Stall (TS) or Loose-Pen (LP).

Variable	Treatment Mean $\pm$ S.E.		Difference of LSMEAN	Ddf	F-Value	P-Value
	LP	TS				
Step Activity (no. steps/d)	818.24 $\pm$ 75.461	748.45 $\pm$ 75.589	69.79 $\pm$ 113.320	6.03	0.38	0.56
Gait						
Swinging Out	-0.12 $\pm$ 0.143	0.14 $\pm$ 0.159	-0.26 $\pm$ 0.218	6	1.39	0.28
Back Arch	-0.02 $\pm$ 0.081	-0.02 $\pm$ 0.090	0.00 $\pm$ 0.123	6	0.00	1.00
Tracking Up	0.00 $\pm$ 0.122	-0.10 $\pm$ 0.136	0.10 $\pm$ 0.186	6	0.29	0.61
Joint Flexion	-0.43 $\pm$ 0.147	0.23 $\pm$ 0.163	-0.66 $\pm$ 0.224	6	8.65	0.03
Asymmetric Step	-0.15 $\pm$ 0.204	0.28 $\pm$ 0.227	-0.43 $\pm$ 0.312	6	1.89	0.22
Reluctance to Bear Weight	0.15 $\pm$ 0.140	0.28 $\pm$ 0.155	-0.13 $\pm$ 0.214	6	0.36	0.57
Overall Gait	-0.26 $\pm$ 0.242	0.31 $\pm$ 0.269	-0.57 $\pm$ 0.369	6	2.40	0.17

better step quality (e.g., longer strides, similar number of steps/leg, better compressibility of walking/standing surface) than TS cows more restricted in their opportunity of movement, yielding a greater net benefit to the cow when moving in this housing environment. Flower *et al.* (2007) reported that cows were more confident in their movements also showed improved joint flexion when walking on a more compressible surface like that of the LP treatment. Sustained exposure to a surface that allowed for comfortable movement in the LP treatment of the current study may have thus translated into significant improvement in joint flexion over the 8-wk dry period when scored in the test corridor.

Furthermore, steps recorded by the pedometers in the TS housing treatment may not have been the same as that of the LP treatment. Pedometers utilized in tie-stalls have been found to be sensitive to more minor step movements made when the cow when engaging in non-locomotor activities (e.g., feeding, interacting with neighbor), recording a step as the cow simply lifting her foot up (IceTag 3D pedometer, Shepley *et al.*, 2017; AfiMilk Pedometer Plus Tag™, Felton *et al.*, 2012). These smaller steps would be expected to occur in both housing systems, but may represent a greater number of the total steps recorded in the TS compared to the LP housing option. Restrictions to the cow's movement can affect locomotion, particularly with regard to her ability to move her elbow and hock joints fully when in motion (Herlin and Drevemo, 1997), thus the longer stride lengths that would be more easily achievable in the LP housing may have provided a fuller range of movement of the leg and benefited joint flexion.

An additional contributing factor for the improvement in joint flexion is may be the composition of the deep-bedded straw bases in the LP treatment compared to the rubber mats with a cover of shavings in the TS with regard to comfort when lying. Deep-bedded straw yards associated had 11.7 % lower prevalence of lameness than free-stall housing (27.1 vs. 38.8 %), with

increasing bedding depth associated with decreasing lameness prevalence (Barker *et al*, 2010). Moreover, improved joint health lying-down ability has been linked in a previous study by Gustafson and Lund-Magnussen (1995) to a more comfortable lying surfaces for strawyard housed dairy cows when compared to cows that were kept housed in tie-stalls. This is consistent with the findings on lying time and lying behaviours reported in Shepley *et al.* (2019) where LP cows showed an improved ability to transition between rising and lying and exhibited a wider variety of lying postures, both of which may indicate improvements of leg and joint health.

5.5. CONCLUSION

Locomotor activity was not increased by the provision of a deep-bedded loose-pen to tie-stall-housed dairy cows during the dry period. This level of activity may be impacted by both the space provided by the housing system in which the cow resides as well as the ways in which the individual cow utilizes the movement opportunity provided to her. Despite a lack of difference in step activity between tie-stall- and loose-pen-housed dry cows, an improvement in joint flexion was observed, suggesting that the loose-pen housing may provides a better walking surface more conducive to improvements in joint health compared to that of cows housed in tie-stalls. Releasing tie-stall housed cows into a deep-bedded loose-housing system can provide increased comfort and ease of movement to the cow during her dry period as well as an opportunity to regain leg health in preparation for her next lactation.

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Supplementary Table S5.1. Variances parameters (σ^2_{cow} , σ^2_e , CS), phenotypic variance (σ^2_p)¹, variable mean ($\bar{x}$)², and coefficient of variation (CV)³ between tie-stall (TS) and loose-pen (LP) treatments for gait variables, taken from the difference between the early and late term of the dry period, and step activity.

Variable	σ^2_{cow}	AR(1)	CS	σ^2_e	σ^2_p	$\bar{x}$	CV (%)
Gait							
Tracking Up	0.013			0.1085	0.1215	0.05	697.1
Swinging Out	0.024			0.1427	0.1667	0.13	314.1
Joint Flexion	0.026			0.1488	0.1748	0.33	127.5
Back Arch	0.003			0.0506	0.0536	0.02	1157.6
Reluctance to Bear Weight	0.022			0.1376	0.1596	0.21	189.0
Asymmetric step	0.086			0.2535	0.3395	0.21	271.9
NRS	0.154			0.3226	0.4766	0.29	241.8
Step Activity	19403	0.7364		45615	65018	783.35	32.6

¹ σ^2_p = the sum of all applicable variance parameters

² $\bar{x}$ = the average between the TS and LP treatment means

³CV = sqrt (σ^2_p) / $\bar{x}$

Supplementary Table S5.2. Mean $\pm$ SEM, variance, and coefficient of variation (CV)¹ for gait variables, taken from the difference between the early and late term of the dry period, and step activity.

Variable	MEAN	SE	σ	CV
Gait				
Tracking Up	0.06	0.094	0.149	2.48
Swinging Out	0.04	0.094	0.149	3.73
Joint Flexion	0.18	0.138	0.322	1.79
Back Arch	0.06	0.064	0.069	1.15
Reluctance to Bear Weight	0.19	0.092	0.142	0.75
Asymmetric step	0.02	0.116	0.227	11.35
NRS	0	0.160	0.436	-
Step Activity	781.79	20.05	50675.73	64.82

¹CV = $\sigma / \bar{x}$

Supplementary Table S5.3. LSMEAN $\pm$ SEM for tie-stall (TS) and loose-pen (LP) treatments, differences between treatment least square means, denominator degrees of freedom for treatment, and p-value denoting significance between treatments for gait variables, taken from the difference between the early and late term of the dry period, and step activity.

Variable	TS, Mean $\pm$ SE	LP, Mean $\pm$ SE	Difference	Ddf	F-Value	P-value
Gait						
Tracking Up	-0.10 $\pm$ 0.134	0.00 $\pm$ 0.122	0.10 $\pm$ 0.186	6	0.29	0.61
Swinging Out	0.14 $\pm$ 0.159	-0.12 $\pm$ 0.143	-0.26 $\pm$ 0.218	6	1.39	0.28
Joint Flexion	0.23 $\pm$ 0.163	-0.43 $\pm$ 0.147	-0.66 $\pm$ 0.224	6	8.65	0.03
Back Arch	-0.02 $\pm$ 0.081	-0.02 $\pm$ 0.090	0.00 $\pm$ 0.123	6	0.00	1.00
Reluctance to Bear Weight	0.28 $\pm$ 0.155	0.15 $\pm$ 0.140	-0.13 $\pm$ 0.214	6	0.36	0.57
Asymmetric step	0.28 $\pm$ 0.227	-0.15 $\pm$ 0.204	-0.43 $\pm$ 0.312	6	1.89	0.22
NRS	0.31 $\pm$ 0.269	-0.26 $\pm$ 0.242	-0.57 $\pm$ 0.369	6	2.40	0.17
Step Activity	818.24	748.45	69.8 $\pm$ 113.32	6.03	0.38	0.56

¹CV = $\sigma / \bar{x}$

CONNECTING STATEMENT 3

Tie-stalls are, indisputably, the most restrictive system with regards to movement opportunity commonly found in the dairy industry. That is not to say that the provision of a less restrictive loose-housing system will necessarily result in increased locomotor activity, as was discussed in detail in Chapter 1 and further confirmed through the results of Chapter 5. The loose-pens in this study were designed to release the cow from her stall and improve her ease of movement, but did not, in the end, result in a difference in step activity. These chapters support the idea that a lack of stall hardware, which provided a more open lying area, and more comfortable flooring may be contributing factors in the improved lying time, rising and lying ability, lying postures, and gait seen in this housing system. What if, then, this housing system was implemented on a larger scale in the form of a deep-bedded strawyard and compared to a free-stall, another stall-based system? Would a larger implementation and presence of herd mates possibly translate to more movement opportunity in one environment compared to the other?

These are some of the questions that are answered in Chapter 5, focusing on how locomotor activity and time budget differs between cows when housed in a strawyard versus when the same cows are housed in free-stalls. As producers transition away from tie-stalls and towards loose-housing systems, the answers to these questions can also make a difference in the outcomes regarding cow health and comfort that the producer anticipated seeing in the change. Chapter 5 also continues the discussion regarding the individuality of cow motivation to engage in locomotor activity when provided with the opportunity to do so. Consistencies in step activity patterns that a cow may exhibit when housed in a strawyard compared to when the same cow is housed in a free-stall are also examined, as is the correlation between step activity indoors and frequency with which cows choose to visit pasture when provided with access.

CHAPTER 6 — THE EFFECT OF FREE-STALL VERSUS STRAWYARD HOUSING AND ACCESS TO PASTURE ON DAIRY COW LOCOMOTOR ACTIVITY AND TIME BUDGET

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6.1 ABSTRACT

Dairy housing systems can have major implications on how freely cows move within their environment and how fully they can express their behavioural repertoire, impacting overall welfare. To ensure housing systems are meeting the needs of the dairy cow, more information is needed on the best method of loose-housing for dairy cows, specifically regarding the provision of locomotor activity and behavior. The objective of this study was to 1) determine whether cows express different locomotor activity and time budget when housed in two different housing types (strawyard - SY vs. free-stall - FS) that provide similar space and 2) measure whether similar locomotor activity and time budgets are expressed in a SY and FS under winter confinement versus under summer conditions with outdoor access. Twenty-four cows were randomly allocated into six groups (n = 4 per group), balanced parity and DIM. Groups were subjected to the FS and SY housing treatments for one week each in a crossover design, with each treatment applied three weeks apart. The same design and procedure were repeated twice: at the end of the winter housing period and at the start of summer after a 6-week grazing period. Locomotor activity and lying data

was collected by pedometers and live observation of cow behavior were carried out 2x/wk for 2h/observation period. The findings revealed no difference between step activity between treatments or seasons. In summer, number of visits to pasture was positively correlated with higher step activity in both the FS ($r = 0.59$, $p < 0.01$) and SY ($r = 0.59$, $p < 0.01$). There was no difference in lying time, but SY cows had more daily lying bouts during summer than FS cows (10.7 vs. 9.2 bouts, $P < 0.001$). Maintenance and locomotor behaviours were not affected by housing treatment, but SY cows tended to socialize more than FS cows in winter (1.7 vs. 0.7 %, $P = 0.06$). Fewer environmental obstructions in the SY may have facilitated expression of non-maintenance behaviours as well ease of lying and rising, thus increasing lying bouts. Cows that were most active indoors accessed pasture more often, suggesting that these cows had a greater motivation to move. While SY benefited over FS housing regarding lying bouts and socialization during winter confinement, further research is needed to determine if these housing options are meeting all cows' movement and activity needs.

Keywords: Behavior; Dairy Cow; Housing; Locomotion; Pasture

6.2 INTRODUCTION

A multitude of distinct housing options exist within the dairy, each of which consists of features that impact the ways in which the cow is able to move within and interact with her environment. This is particularly true for loose-housing systems, which allow the cows to move freely, but still within confines of an indoor environment. Most commonly selected for loose-housing systems is the free-stall, but other methods of loose-housing, such as a deep-bedded pack, are increasing in popularity (Barberg *et al.*, 2007). The use of deep-bedded packs, such as strawyards or compost bedded packs, has the potential to increase lying time (Fregonesi and Leaver, 2000; Endres and Barberg, 2007) and leg health (Haskell *et al.*, 2007), which may impact

the locomotor ability and activity of the cow. Deep-bedded packs provide comfortable and spacious lying areas that facilitate better rising and lying abilities (Fregonesi *et al.*, 2009) and good walking surfaces (i.e. good traction, compressibility; Jungbluth *et al.*, 2003). Free-stalls, by contrast, provide obstacles (i.e. stall hardware) that may impact lying ability (Fregonesi *et al.*, 2009) and solid walking surfaces (i.e. concrete, slatted floors) outside of the stall tend to be less suited for easy movement (i.e. hard, abrasive, and/or slippery; Franco-Gendron *et al.*, 2016). There is no clear information, however, on how different loose-housing systems, such as deep-bedded packs and free-stalls, compare with regard to the level of locomotor activity the cows are able to engage in and the impact on the overall time budget of the cows.

Pasture, by contrast, provides substantially more space for the cows to move freely (between 1 and 13 km/d; Phillips, 2013). Access to pasture, even for short periods of time, may increase leg health (Hernandez-Mendo *et al.*, 2007), thus improving the cow's locomotor ability. Additionally, access to pasture has been shown to increase lying time over indoor cubicle systems (Olmos *et al.*, 2009) and facilitates cow rising and lying abilities (Lidfors, 1989) compared to indoor housing conditions. This might contribute to the increase in pasture access for cows with previous pasture experience (Shepley *et al.*, 2017). The potential impact of previous exposure to pasture access and the potential motivation for continued access to pasture may lead to a difference in locomotor activity displayed indoors.

We have hypothesized that housing system with a softer, more compressible walking surface and fewer environmental obstructions will increase step activity and improve social and lying behaviours in cows when in these treatments. To test these hypotheses, our study had two primary objectives: 1) to determine whether cows express different locomotor activity and time budgets when housed in two different housing types (strawyard vs. free-stall) that provide similar

space across two different seasons (winter and summer) and 2) to determine if there is a relationship between the number of visits cows take to pasture in the summer and their step activity when in the strawyard and free-stall housing treatments.

6.3 MATERIALS AND METHODS

6.3.1. Animals

Forty-eight lactating Holstein dairy cows, divided evenly between two start dates (Winter and Summer, $n = 24$ cows/start date), were selected from the herd at the Institut de Genech research dairy facility (Genech, France). Cows were randomly allocated into six groups of four cows, blocked by parity (mean parity $\pm$ SD, Winter: 1.7 ± 0.80 ; Summer: 1.8 ± 0.99) and DIM (mean DIM $\pm$ SD, winter: 139.6 ± 81.89 DIM; start 2: 168.3 ± 66.55). As lameness was determined to have a potential impact on locomotor activity, all cows selected for the study were evaluated for gait enrollment and only sound cows (scored ≤ 2 on a 1-5 NRS system; Flower and Weary (2006)) were selected for use in the study. Additionally, cows that presented signs of health problems prior at the time of selection were likewise not chosen. This study conformed to French guidelines for approval of animal use in research. As per the official obligation set forth for French universities, a member of the university certified for animal care oversaw all aspects of animal use and care over the course of the study.

6.3.2. Housing and management

Cows were subjected to three different indoor housing areas during the course of the study. All cows had previous exposure to each housing type prior to enrollment in the study. The free-stall (FS) treatment provided $11.8 \text{ m}^2/\text{cow}$ of surface area and was comprised of $8.0 \text{ m}^2/\text{cow}$ of concrete flooring topped with rubber mats and at least $1.25 \text{ cubicle}/\text{cow}$ (bed length = 2.5 m , stall width = 1.2 m) with a Pasture Mat base (Promat, Woodstock, Canada) and fine layer (120

g/cubicle/d) of chopped mischanthus as top bedding. The strawyard (SY) treatment provided 12.6 m²/cow with a total area of 4.8 m²/cow of concrete flooring topped with rubber mats and a total lying area of 7.5 m²/cow. The lying area was deep-bedded straw, bedded at a depth of 20-25 cm. Both treatments offered similar amounts of space per cow based on stocking density. The cow's normal housing system, a free-stall, was a non-treatment housing option used between treatment applications to ensure that cows entered each treatment under the same conditions. The non-treatment housing provided a minimum of 12 m²/cow of total surface area, comprised of 7.3 m²/cow of a combination of concrete flooring topped with rubber mats and asphalt and a minimum of 1.5 cubicles/cow (same stall size, base, and bedding as used in FS treatment area). All indoor housing was located in the same barn and subject to the same environmental conditions (e.g., light, ventilation, temperature). In the summer, cows in the non-treatment area were also provided free access to pasture. All housing areas had free access to an automatic milking system (AMS, DeLaval Inc., Tumba, Sweden) and cows were sorted into their designated housing area after each milking via a smart selection gate (DeLaval Inc., Tumba, Sweden). Both in winter and summer, the cows received a TMR ration, adapted based on pasture access. An addition of 3 kg/cow/day of concentrate was included in the AMS.

6.3.3. Experimental design

The first start date, carried out at the end of the winter season after an extended period of indoor confinement, was conducted over a six-week period from March to April 2017. The second start date, which was carried out during the summer after cows have been on pasture for six weeks, occurred over a six-week period from June to July 2017. Using a crossover design, cows in each group were housed in both the FS and the SY treatment areas for one week. Between each housing treatment, cows were housed for two weeks in their normal herd housing in the non-treatment free-

stall area (free-stall with herd = FSH; winter) or in the non-treatment free-stall area with free access to pasture (free-stall, herd plus pasture = FSHP; summer). The use of the non-treatment housing was to ensure that all cows entered each treatment area under the same previous housing conditions. Application of the treatment sequence was done randomly for period 1 (weeks 1-3) during which time three groups were exposed to the FS treatment and three were exposed to the SY treatment for one week per group with the application of the treatment housing for each group staggered over the three weeks (Table 6.1).

Table 6.1. Crossover design applied in the study with the order of treatment application for each group of 4 lactating dairy cows across the 6-wk study period for both the winter (top) and summer (bottom) start dates.

Winter						
	Period 1			Period 2		
Treatment	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6
SY	Group 1	Group 6	Group 3	Group 4	Group 5	Group 2
FS	Group 4	Group 5	Group 2	Group 1	Group 6	Group 3
Summer						
	Period 1			Period 2		
Treatment	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6
SY	Group 5	Group 4	Group 6	Group 3	Group 1	Group 2
FS	Group 3	Group 1	Group 2	Group 5	Group 4	Group 6

6.3.4. Measures

Step activity (number of steps) and lying activity (lying time, lying bout frequency) were automatically recorded in 15-minute intervals using a 3D pedometer (IceQube, IceRobotics, Edinburgh, Scotland) mounted on the right rear leg of the cow for the six-week duration of each

start date. Data was averaged at the day-level for each cow. Number of visits to pasture was also measured by a smart selection gate when cows were housed in the FSHP treatment in the summer.

Live behavioural observations occurred on the same day each week, twice per week for two hours per observation session with one session occurring the morning (7:00 h – 9:00 h) and one occurring in the afternoon (15:00 h to 17:00 h) for a total of four hours of observations per week. Times were selected to coincide with the times where cows were found to be most active on the research farm. Observations were carried out by two trained observers in each session using live instantaneous scan sampling at 2-minute intervals for each housing treatment. Table 6.2 provides a description of the behaviours recorded during each session. These behaviours were subdivided into five main categories: posture (lying or standing), maintenance, locomotor/exploratory, socialization, and other. Behaviours were recorded at the cow level in each group with cows identified using colored bands on all four feet to ensure visibility of the identifier throughout the observation session. The percentage of time that the cow was observed performing each activity was recorded and averaged at the week level. Inter-observer reliability was carried out to ensure accuracy between observers for all behaviours used with an average percent agreement of 98 % (range: 95.7 – 100 %) and an average weighted kappa (K_w) of 0.90 (range: 0.66-1.00).

6.3.5. Statistical Analysis

All analyses were run in a statistical analysis software, SAS 9.4 (SAS Institute, 2008). Analyses of pedometer data was conducted at the group level. Although cows had previous exposure to each housing treatment, only step and lying activity recorded on days 4-7 were used in the analysis to account for any differences resulting from the relocation to the treatment housing. Four days has been cited in previous literature (Vasseur *et al.*, 2012; Ito *et al.*, 2009) as being a reliable duration for recording of pedometer data. A post hoc comparison using Scheffé adjustment

Table 6.2. Ethogram of the behavior categories recorded for each dairy cow when in the Free-stall (FS) and Strawyard (SY), including the behaviours included in each category and their definitions.

Behavioural Categories	Description	Adapted from
Posture		
Lying	Positioned with either flank in contact with the ground	Palacio <i>et al.</i> , 2015
Standing	Positioned with all four feet on the ground	Haley <i>et al.</i> , 2000
Maintenance		
Milker		
Waiting for milker	Standing near the milk parlor door, facing the parlor entrance	–
In milk parlor	In milk parlor, cow is not visible in the barn at this time	Haley <i>et al.</i> , 2000
Feeding		
Eating	Head through head gate at feed bunk, head can be up or down in the bunk, mastication need not be observed	Bikker <i>et al.</i> , 2014
Licking mineral	Licking mineral stone	–
Sniffing/moving feed	Sniffing at feed/mineral stone or moving feed around in feed bunk	Loberg <i>et al.</i> , 2004
Licking Floor	Licking floor of feed bunk	–
Drinking	Cow is within 1 m of water trough, facing the water, cow does not have to be actively consuming water	Palacio <i>et al.</i> , 2015
Rumination	Masticating away from the feed bunk	Bikker <i>et al.</i> , 2014
Sleep	Lying down with head resting against side of the body	Ternman <i>et al.</i> , 2014
Locomotor/Exploratory		Loberg <i>et al.</i> , 2004 ¹
Locomotion		
Walk	Moving with 2-3 feet on ground in a four-beat gait in action unrelated to other behaviours (e.g., social, aggression)	
Trot	Moving with 2 feet on ground in a two-beat gait in action unrelated to other behaviours	
Exploration		
Sniffing Environment	Sniffing the ground/object in the environment when outside of feed bunk	
Licking Environment	Licking the ground/object in the environment when outside of the feed bunk	

¹All subcategories of a behavior/behavioural category are adapted from the same reference

Table 6.2. Continued.

Behavioural Categories	Description	Adapted from
Socialization		Krohn, 1994 ¹
Positive Socialization		
Allo-grooming	Cow licking /being licked by other cow	
Social rubbing	Rubbing head on/being rubbed on by the head of another cow	
Social sniffing	Cow's nose if within 10 cm of other cow	
Play	Two cows non-aggressively pushing head/body against each other without intent to mount or groom	
Aggression/Submission		
Fighting	Head-to-head with physical contact	
Threatening Gesture	Head lowered, eyes and body focused on other cow	
Chasing	Cow moving after another cow, displacing other cow	
Submission/Avoidance	Moves away from aggressive behavior of other cow	
Other		
Idle	Standing/lying still without any other listed behaviours occurring	Haley <i>et al.</i> , 2000
Self-Grooming		Loberg <i>et al.</i> , 2004 ¹
Licking Self	Licking a part of own body	
Rubbing against item	Rubbing head or body against an item in the barn	
Other	Behaviours that do not fall into any of the above listed categories	–

¹All subcategories of a behavior/behavioural category are adapted from the same reference

was applied to the step and lying data analyses. Observational data, averaged by week, was condensed into five behavioural categories for analysis: posture, maintenance, locomotor/exploratory, socialization, and other. These behaviours were likewise analyzed at the group level. A mixed model procedure (PROC MIXED and LSMEANS) was used for all analyses, following the model:

$$\gamma_{ijkm} = \mu + \text{sequence}_i + \text{group}_{ij} + \text{period}_k + \text{treatment}_m + e_{ijkm}$$

where $\gamma_{ijk\ell m}$ represents the observation, μ is the population mean, sequence_i is the fixed effect of the i th sequence ($i = \text{SYFS}$ or FSSY), group_{ij} is the random effect of the j th group ($j = 1, 2, 3$) in the i th sequence, period_k is the fixed effect of the k th period ($k = 1, 2$), treatment_ℓ is the fixed effect of the ℓ th treatment ($\ell = \text{SY}$ or FS) and $e_{ijk\ell m}$ is the random error.

A mixed model was also used to analyze the differences for similar housing types between the summer and winter, adding season as a fixed effect of the within which sequence, period and group were nested, following the model:

$$\gamma_{ijk\ell mn} = \mu + \text{season}_i + \text{sequence}_{ij} + \text{group}_{ijk} + \text{period}_{im} + \text{treatment}_\ell + \text{treatment}_\ell * \text{season}_i + e_{ijk\ell mn}$$

An additional effect of treatment by season was added to determine the effect of the i th season ($i = \text{winter}$ or summer) on the ℓ th treatment ($\ell = \text{SY}$ or FS). Significant differences were indicated at $P < 0.05$. A Pearson correlation (PROC CORR) was run at the cow level to determine the relationship between number of steps recorded in each treatment area and the number of visits to pasture for that cow when she was in the FSHP area.

6.4 RESULTS

6.4.1. Step Activity

There were no significant differences in step activity between the SY and FS housing areas (Table 6.3). In addition, no differences in step activity were found between seasons for SY ($P = 0.61$) nor FS ($P = 0.31$) housing treatments. The number of visits to pasture during the summer season were moderately positively correlated with the number of steps taken by the cow in both the SY ($r = 0.59$, $\rho < 0.01$) and the FS ($r = 0.59$, $\rho < 0.01$) areas, with a higher number of steps associated with a higher number of visits to pasture (Figure 6.1).

6.4.2. Lying Activity

SY-housed cows had a higher overall total number of lying bouts ($P < 0.01$; 10.6 ± 0.20 vs. 9.5 ± 0.20 bouts/day; SY vs. FS, respectively), owing largely to the higher average number of lying bouts in SY-housed dairy cows in the summer compared to FS-housed cows (10.9 ± 0.29 vs. 9.3 ± 0.36 , respectively, $P < 0.001$; Table 6.3). The total number of lying bouts did not differ between season for the SY ($P = 0.11$) or FS treatment ($P = 0.39$). Lying time was not significant different between housing systems. A season effect was found for overall lying time, with higher lying times recorded in the winter than in the summer (12.5 ± 0.25 vs. 11.2 ± 0.25 ; $P < 0.01$). With regard to the treatment*season effect, lying time showed a tendency to be higher in the winter than in the summer for the FS treatment (12.4 ± 0.30 vs. 11.18 ± 0.30 ; $P = 0.07$).

Table 6.3. Mean, minimum and maximum values, and residual error of step and lying data, by season, for dairy cows in the Strawyard and Free-stall treatment areas.

	Strawyard			Free-stall			P-Value
	Mean $\pm$ SD	Min	Max	Mean $\pm$ SD	Min	Max	
Step (steps/d)							
Winter	1073.6 $\pm$ 71.04	905.8	1198.6	1179.4 $\pm$ 71.04	962.6	1523.2	0.16
Summer	1016.1 $\pm$ 84.58	855.2	1351.7	1062.2 $\pm$ 84.58	797.7	1270.3	0.59
Lying Bout (bouts/d)							
Winter	10.2 $\pm$ 0.35	9.3	10.8	9.6 $\pm$ 0.35	8.4	10.7	0.27
Summer	10.9 $\pm$ 0.22	10.2	11.4	9.29 $\pm$ 0.22	8.4	9.8	< 0.001
Lying Time (hr/d)							
Winter	12.6 $\pm$ 0.27	11.5	13.6	12.4 $\pm$ 0.27 ^a	11.9	12.9	0.59
Summer	11.5 $\pm$ 0.32	10.7	12.1	11.2 $\pm$ 0.32 ^b	9.8	12.6	0.52

^{a,b}Denotes tendency for a difference between seasons ($P < 0.1$)

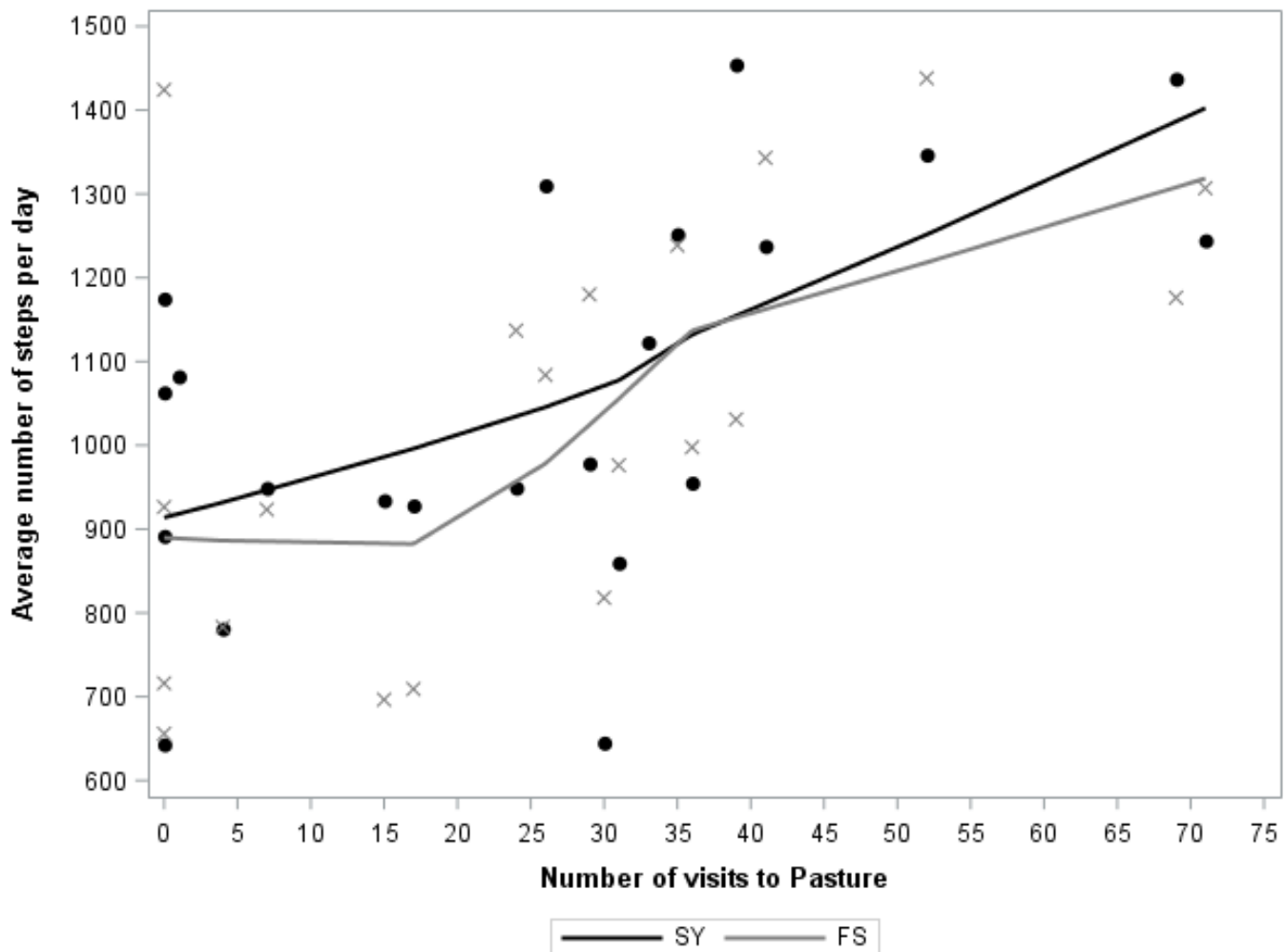


Figure 6.1. Association between the average number of steps per day for each cow when housed in the Strawyard (SY, ●) and Free-stall (FS, ×) treatment areas and the total number of visits to pasture when housed in the Free-stall herd housing with free access to pasture (FSHP) non-treatment area. Trend lines for the correlations between step activity and pasture visits by housing system are indicated for both SY (black) and FS (grey).

6.4.3. Behavioural Observations

There were no effects of housing system on maintenance behaviours within each season (Table 6.4). Locomotor/exploratory behaviours were numerically higher in the SY for both seasons, but non-significant (4.4 % vs. 2.7 % and 3.2 % vs. 1.7 % for SY vs. FS in the winter and summer, respectively). Socialization tended to be higher (1.7 % vs. 0.7 %, $P = 0.06$) in the SY treatment area than in the FS area during the winter. There was a season*treatment effect for

socialization in SY cows, with socialization significantly higher during the winter than the summer (1.7 % vs. 0.8 %, $P = 0.04$).

Table 6.4. Mean $\pm$ S.E. for time budget of cows, presented as a percentage of time observed for each of the five behavioural categories, in the strawyard (SY) and free-stall (FS) treatment area for both the winter and summer seasons.

Behavior	Season	Strawyard	Free-stall	P-value
Posture				
Standing	Winter	75.1 $\pm$ 3.23	70.7 $\pm$ 3.23	0.36
	Summer	81.0 $\pm$ 3.59	74.0 $\pm$ 3.59	0.22
Lying	Winter	24.9 $\pm$ 3.23	29.3 $\pm$ 3.23	0.36
	Summer	18.7 $\pm$ 3.51	25.8 $\pm$ 3.51	0.21
Maintenance	Winter	80.8 $\pm$ 1.80	81.9 $\pm$ 1.80	0.68
	Summer	79.9 $\pm$ 2.26	80.9 $\pm$ 2.26	0.77
Locomotor/ Exploratory	Winter	4.4 $\pm$ 0.8	2.7 $\pm$ 0.8	0.26
	Summer	3.2 $\pm$ 0.9	1.7 $\pm$ 0.9	0.13
Socialization	Winter	1.7 $\pm$ 0.3 ^a	0.7 $\pm$ 0.3	0.06
	Summer	0.8 $\pm$ 0.3 ^b	0.9 $\pm$ 0.3	0.63
Other	Winter	13.0 $\pm$ 1.5	14.7 $\pm$ 1.5	0.34
	Summer	15.7 $\pm$ 1.5	16.1 $\pm$ 1.5	0.87

^{a,b} Means with different superscript letters in the same column differ significantly ($P < 0.05$)

6.5 DISCUSSION

We hypothesized that the open areas created by a strawyard housing system would lead to higher locomotor activity of cows. Other studies have suggested that housing systems utilizing deep-bedded packs would increase the cow's freedom of movement (Endres and Barberg, 2007), but they have not documented the difference in step activity. Our study found no significant differences in step activity between the SY and FS housing treatment areas and, in fact, had numerically lower step activity in the strawyard than in the freestall, contradicting our initial hypothesis. The size and layout of the housing areas were similar between the two treatments which may explain this lack of difference between treatment areas. In a study by Telezhenko *et al.* (2012), the size of the housing area had an impact on overall locomotor activity in free-stall dairy

cows, therefore, providing similarly spaced housing options would yield similar step activity. However, strawyards provide a softer surface on which the cow can walk. Surfaces with higher compressibility have been shown to increase the step length, walking speed, and locomotor activity of dairy cows, with step lengths more similar to that of a cow on pasture and distance walked increasing by an estimated 1,000 m/d (Jungbluth *et al.*, 2003). On the other hand, the corridors for both treatment areas in the current study were covered with rubber mats which, when kept properly clean and dry, offer a compressible surface with good traction that impact cow locomotion in comparable ways to deep-bedded options (Telezhenko and Bergsten, 2005), leading to the lack of differences in step activity.

Interestingly, when observing the relationship between visits to pasture and step activity, we found step activity to be higher in both housing areas for cows that were recorded as having more visits to pasture over the 6-week summer start date. This could indicate a greater motivation for movement in individual cows that utilize pasture more frequently which, in turn, resulted in higher step activity indoors for these cows when compared to cows that visited pasture less frequently. By comparison, a study by Dohme-Meier *et al.* (2014) found that free-stall cows with pasture access walked nearly 2.7-fold more than cows without access (4,064 vs. 1,506 steps/day, respectively), confirming that pasture leads cows to engage in more locomotor activity compared to cows confined to free-stall housing. Furthermore, studies have shown that cows have varying degrees of motivation for pasture and, possibly, the movement opportunity it provides. For instance, when cows are exposed previously to pasture, they are more likely to prefer to be at pasture over an indoor free-stall (Shepley *et al.*, 2017). As the number of visits varied greatly between individual cows in the current study, it is also possible that individuals vary greatly in

their general locomotor needs. However, to the authors' knowledge, no such investigation into the topic of locomotor needs for dairy cows has been conducted.

According to Keeling and Jensen (2002), frustration is the likely by-product of inhibiting an animal's ability to perform behaviours that it is motivated to perform. With considerable differences in motivation and locomotor requirements, it is plausible to envisage that cows that visit pasture more frequently in the summer may have increased frustration at the level of restriction of the indoor housing areas to their motivation for movement, increasing step activity as a product of this frustration. Available studies, however, focus on the impact of restrictive housing as it relates to tie-stall systems, with little information on the potential restrictive nature of loose-housing systems.

Less restrictive environments free of structural impediments such as stall hardware promote increased lying bouts (Hernandez-Mendo *et al.*, 2007) as the cow is provided more space for increased lying comfort and is simultaneously less encumbered by physical obstacles that hinder her rising and lying abilities (Shepley *et al.*, in press). The results of the current study confer in part with these findings, with the SY area yielding a significantly higher number of lying bouts compared to the FS treatment during the summer. The elimination of hardware and obstructions that are characteristic of free-stall housing may have contributed to the ease with which the cow is able to rise and lie down (Fregonesi *et al.*, 2009), thus increasing her willingness and or ability to rise and lie more often. Similarly, lying time is also a commonly used indicator of the level of comfort, with a decrease in lying time possibly indicative of lower comfort levels generated by the cow's environment (Munksgaard *et al.*, 2005). In the current study, there were no differences between treatments for lying time which were an anticipated outcome of the SY housing. Fregonesi and Leaver (2000) found similarly variable results for lying time when comparing strawyard and

free-stall housing systems with significantly higher lying time recorded for strawyard cows during one experiment (13.6 – 14.1 vs. 11.9 – 13.2 hr/d, strawyard vs. free-stall, respectively), but finding no significant differences in the subsequent experiment. It was suggested by Fregonesi and Leaver (2000) that lying time may have been influenced by strawyard design, leading to increased disturbances of lying.

Behaviours typically regarded as maintenance behaviours (e.g., feeding, ruminating, and drinking) were not significantly affected by housing type, suggesting the cow's physiological needs are being met equally in both housing areas. Locomotor/exploratory behaviours are impacted by a number of factors such as the need for resources, social behaviours, and the ability of the housing environment to meet the cow's spatial needs and provide an adequate walking surface (Zeeb, 1983). The lack of significant difference in locomotor/exploratory behavior could be attributable to the lack of other behavioural difference seen, particularly those related to maintenance that consume a majority of the cow's time budget. This study was limited in the duration and type of behavioural observation which may have led to an underrepresentation of locomotor/exploratory behaviours in each housing type and may also account for the lack of treatment difference for socialization. While changes in housing may also lead to a disruption of normal behavioural expression and alter observational results, past research has found that behaviours for dairy cows return to baseline levels by the second day following regrouping which corresponds with the first observation session in the current study (von Keyserlingk *et al.*, 2008). Interestingly, there was a response in social behaviours as a result of season, with SY cows soliciting social interactions more in the winter. Fregonesi and Leaver (2000) found a similar increase in social behaviours and environmental exploration when cows were moved to a strawyard from a free-stall, suggesting that the strawyard provided more flexibility for the cow

and facilitated social behaviours. Much like our findings, Krohn (1994) found that social behaviours were lower for cows provided continuous access to the outdoors, particularly for agonistic interactions which occurred at a fraction of the rate for cows with continuous outdoor access than cows provided only 1 hr/d outdoors. The lower number of social interactions during the summer may have been a result of increased behavioural expression when in FSHP area which was sufficient for fulfilling the animal's social needs.

6.6 CONCLUSION

No housing environment tested yielded a greater level of locomotor activity in the cows than the other. Nevertheless, the increased level of step activity amongst cows that accessed pasture more frequently indicates a potential individual motivation and behavioural need to perform locomotor activity. Strawyard housing showed evidence of increased lying bouts which may be attributed to increase comfortable and ability to transition between lying and standing in this housing system. Furthermore, the strawyard environment may have facilitated the expression of social behaviours under winter housing. The findings of this study suggest that strawyards may offer some advantages over free-stall systems, but that, perhaps, if we wish to fulfill key behavioural needs (e.g., resting, locomotor activity, social interactions), future investigation into these housing systems should be done in combination with outdoor access.

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Supplementary Table S6.1. Variances parameters (σ^2_{cow} , σ^2_{e} , CS), phenotypic variance (σ^2_{p})¹, variable mean ($\bar{x}$)², and coefficient of variation (CV)³ between tie-stall (TS) and loose-pen (LP) treatments for gait variables, taken from the difference between the early and late term of the dry period, and step activity.

Variable	$\sigma^2_{\text{group(sequence)}}$	σ^2_{e}	σ^2_{p}	$\bar{x}$	CV (%)
Step					
Winter	18976	11304	30280	1126.51	15.4
Summer	24119	18804	42923	1039.17	19.9
Lying Time					
Winter	0	0.5325	0.5325	11.92	6.1
Summer	0	0.6157	0.6157	11.33	6.9
Lying Bouts					
Winter	0	0.7479	0.7479	9.95	8.7
Summer	0.1841	0.1156	0.2997	10.12	5.4
Maintenance					
Winter	0	19.5413	19.5413	81.39	5.4
Summer	0	28.7388	28.7388	80.39	6.7
Locomotion/Exploration					
Winter	0	6.1969	6.1969	3.54	70.3
Summer	0	2.1528	2.1528	2.44	60.3
Socialization					
Winter	0.1697	0.503	0.6727	1.22	67.4
Summer	0.1731	0.086	0.2591	0.86	59.2
Other					
Winter	0	8.2337	8.2337	13.85	20.7
Summer	0	18.7052	18.7052	15.88	27.2

¹ σ^2_{p} = the sum of all applicable variance parameters

² $\bar{x}$ = the average between the TS and LP treatment means

³CV = $\sqrt{\sigma^2_{\text{p}}}/\bar{x}$

Supplementary Table S6.2. LSMEAN $\pm$ SEM for tie-stall (TS) and loose-pen (LP) treatments, differences between treatment least square means, denominator degrees of freedom for treatment, and p-value denoting significance between treatments for gait variables, taken from the difference between the early and late term of the dry period, and step activity.

Variable	FS, Mean $\pm$ SE	SY, Mean $\pm$ SE	Difference	Ddf	F-Value	P-value
Step						
Winter	1179.4 $\pm$ 71.04	1073.6 $\pm$ 71.04	105.8 $\pm$ 61.38	4	2.97	0.16
Summer	1062.2 $\pm$ 84.58	1016.1 $\pm$ 84.58	46.1 $\pm$ 79.17	5	0.34	0.59
Overall	1120.8 $\pm$ 55.39	1044.9 $\pm$ 55.39	75.9 $\pm$ 50.78	9	2.224	0.17
Lying Time						
Winter	12.4 $\pm$ 0.30	12.6 $\pm$ 0.30	0.2 $\pm$ 0.42	8	0.32	0.59
Summer	11.2 $\pm$ 0.32	11.5 $\pm$ 0.32	0.3 $\pm$ 0.45	9	0.45	0.52
Overall	11.8 $\pm$ 0.21	12.1 $\pm$ 0.21	0.3 $\pm$ 0.30	17	0.76	0.49
Lying Bouts						
Winter	9.6 $\pm$ 0.35	10.2 $\pm$ 0.35	0.6 $\pm$ 0.50	8	1.40	0.27
Summer	9.3 $\pm$ 0.22	10.9 $\pm$ 0.22	1.6 $\pm$ 0.20	5	70.37	< 0.001
Overall	9.5 $\pm$ 0.20	10.6 $\pm$ 0.20	1.1 $\pm$ 0.29	17	15.04	< 0.01
Maintenance						
Winter	81.9 $\pm$ 1.80	80.8 $\pm$ 1.80	1.1 $\pm$ 2.55	8	0.19	0.68
Summer	80.9 $\pm$ 2.26	79.9 $\pm$ 2.26	1.0 $\pm$ 3.28	8	0.10	0.77
Overall	81.4 $\pm$ 1.44	80.4 $\pm$ 1.44	1.1 $\pm$ 2.07	16	0.26	0.61
Locomotion/ Exploration						
Winter	2.7 $\pm$ 1.0	4.4 $\pm$ 1.0	1.7 $\pm$ 1.44	8	1.46	0.26
Summer	1.7 $\pm$ 0.62	3.2 $\pm$ 0.62	1.5 $\pm$ 0.90	8	2.82	0.13
Overall	2.2 $\pm$ 0.60	3.8 $\pm$ 0.60	1.6 $\pm$ 0.86	16	3.56	0.08
Socialization						
Winter	0.7 $\pm$ 0.33	1.7 $\pm$ 0.33	1.0 $\pm$ 0.41	4	6.47	0.06
Summer	0.9 $\pm$ 0.21	0.8 $\pm$ 0.21	0.1 $\pm$ 0.22	2.12	0.31	0.63
Overall	0.8 $\pm$ 0.20	1.3 $\pm$ 0.20	0.5 $\pm$ 0.25	8.64	3.42	0.09
Other						
Winter	14.7 $\pm$ 1.17	13.0 $\pm$ 1.17	1.7 $\pm$ 1.66	8	1.01	0.34
Summer	16.1 $\pm$ 1.82	15.7 $\pm$ 1.82	0.4 $\pm$ 2.65	8	0.03	0.87
Overall	15.4 $\pm$ 1.08	14.3 $\pm$ 1.08	1.05 $\pm$ 1.54	16	0.46	0.51

GENERAL DISCUSSION AND CONCLUSION

The concept of movement opportunity presented in this study arose from an unsatisfactory presentation of what is considered to be exercise for dairy cows in the literature. When a human lifts weights or goes for their regular Soul Cycle class, we can state that this is exercise. When we take our dogs for walks, ride our horses, have our cats run laps around the living room chasing after laser pointers – this is exercise. When we open a free-stall barn door to provide access to an outdoor yard, this could be exercise, though, can this truly be considered ‘exercise’ if one animal runs like she is training for a marathon and another looks on idly as she stands in place and chews cud? Short of walking or herding cows, all we can provide cows and, similarly, other livestock species with is the opportunity to increase her level of movement – in other words, provide movement opportunity.

How we provide movement opportunity to dairy cows and the myriad of elements within the cow’s environment, including the cow herself, plays a vital role in the expected outcomes on the cow’s health, comfort, and overall well-being. To start, locomotor activity can be influenced to a degree by housing environment, with cows provided more space in the free-stall and strawyard housing in Chapter 6 presenting higher step activity than the cows in Chapters 4 and 5. Surprisingly, tie-stall-housed cows were found to only have slightly lower step activity compared to loose-pen-housed cows, suggesting that simply untethering the cow from her stall is not enough to incite greater levels of movement and that, perhaps, consideration for environmental complexity is warranted. This does, however, bring up an important note in regard to what constitutes a step, as this is likely to also have impacted these results. As was outlined in Chapter 3, a step taken in a tie-stall is not always the same as that which is taken in a loose-housing system, with steps registered by the IceTag pedometers used in Chapters 3 through 5 in this thesis only requiring that

the cow lifts a majority of her foot off the ground. Compare this to a full stride that can be taken in even marginally larger environments like the loose-pen when the cow is released from the tie-stall and it can be postulated that a higher proportion of steps taken in the tie-stall would be less impactful with regard to overall movements in the cow than loose-housing provides. Equally notable is the lack of differences between the strawyard and free-stall in Chapter 6, which both had similar design layouts and which both met the requirements for their respective housing types for space per cow. This suggest that, while increasing the housing size may increase locomotor activity, if requirements for space per cow and stocking density are met, neither type of loose-housing can be expected to provide more locomotor activity than the other.

There is evidence found in this thesis that it is the housing characteristics, not just the level of locomotor activity, for indoor housing systems that provide benefits to the cow presented in Chapters 3 through 5, with space, lack of stall hardware, and flooring type possibly serving as the stronger contributing factors in the differences found in the other variables tested. This is seen in the improvement in gait, especially the significant improvement in joint flexion, found in Chapter 4 for the loose-pen-housed cows even when no differences were found in locomotor activity. As noted previously, this could be due, in part, to the way that a step is recorded by the technology used, but it is more strongly supported by the pen flooring. The deep-bedded loose-pen offered a softer flooring for walking which may have allowed the cow to move with greater ease in her environment, improving the movement of her leg joints. This could also be due to the improvements in rest quality found in Chapter 4, with greater space allowing the cow to extend her legs more often when lying down, thus offering more movement to the leg joints, and the more cushioned flooring and lack of stall hardware allowing the cow to move between lying and standing with greater ease and less pressure on her carpal joints.

The differences in lying bouts found in Chapter 6 and the substantial differences in rising and lying ability and lying postures presented in Chapter 4 suggest that movement opportunity unrelated to locomotor activity may still be greater for cows in the non-stall-based treatments in both of these studies. The lack of stall hardware in Chapter 4's loose-pens led to a decreased the number of contacts that the cow made with her environment, improving ease of movement when transitioning between standing and lying. Numerically reduced time needed to lie down supports this idea. The loose-pen cows also used more space when lying down to extend their legs and exhibit more rest postures. Moreover, this was done without impeding on another cow's space, as occurred in tie-stall housed cows. As a result, cows in non-stall-based housing are granted a greater level of movement opportunity when lying down. While not measured in Chapter 6, it would be expected that the cows in the free-stall would be similarly impacted by the limitations set by the amount of space in their stall. This may have contributed to the lower number of lying bouts recorded in this treatment, as the cows had a reduced ability to move with ease between the standing and lying position.

The ability to exhibit choices through behaviours and preferences may also be related to the level of movement opportunity the housing systems examined in this thesis provided. Cows in loose-pens took longer to choose where in their pen they would lie down, having the opportunity to move between different areas to select the location that best suited her preferences and or needs. Cows in the strawyard treatment in Chapter 6 tended to engage in social behaviours more than those in free-stalls, with the open space provided by the deep-bedded pack possibly being more conducive to such behaviours.

That also leads to the topic of individual cow needs. One of the limitations to the studies presented in Chapters 4 to 6 and to most studies that look at the effects of providing increased

movement opportunities to cows, particularly through outdoor access, is that it is done at the group or herd level. When the option is between production pasture, as is seen in many of the studies stating to look at exercise (Table 1.1), and indoor housing, the space, grazing opportunity, and walking/lying surface on pasture are all but expected to yield higher locomotor activity, gait improvement, and behavioural differences. In indoor housing and housing that provides outdoor access, however, locomotor activity may be influenced by the individual cow's motivation to use the movement opportunity provided. For instance, when viewed at the individual level, disregarding treatment, we saw that higher step activity in both tie-stall and loose-pen cows in the study presented in Chapters 4 and 5 tended to correlate with the cows that exhibited the greatest improvement in overall gait. Similarly, in Chapter 6, cows that exhibited higher levels of step activity in both the free-stall and the strawyard took more visits to the outdoor exercise pastures when access was provided during non-treatment weeks. Cows that make greater use of the level of movement opportunity provided are, thus, more likely to attain related benefits, while alternative methods for ensuring the health and welfare of the other cows may need to be considered if similar results are to be expected of all cows.

Developed in 2009, the Canadian Dairy Code of Practice set forth guidelines for the housing, management, and overall care of dairy cattle in Canada. Through the ProAction® Initiative, Canada will be seeing the implementation of these guidelines as auditable requirements for minimal standards on commercial dairy farms. Absent from these Codes of Practice are recommendations regarding the importance of providing dairy cows with an environment in which she is has the opportunity to move and express the level of locomotor activity that she is motivated to perform within her environment. There are also very few recommendations regarding the use of pasture or other forms of outdoor access to supplement indoor housing practices or of their

potential benefits to, among other things, cow leg health, behavior, and comfort. This thesis presents some information regarding the expectations producers can have regarding only a selection of indoor housing options in the dairy industry, but also touches on the need to think outside of the box or, perhaps even, outside of the barn, to ensure that the housing provided is suitable for a cow in motion.

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