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THE ASSESSMENT OF RISING AND LYING DOWN BEHAVIOURS OF DAIRY COWS IN CUBICLE HOUSING SYSTEMS WITH REGARD TO ANIMAL WELFARE

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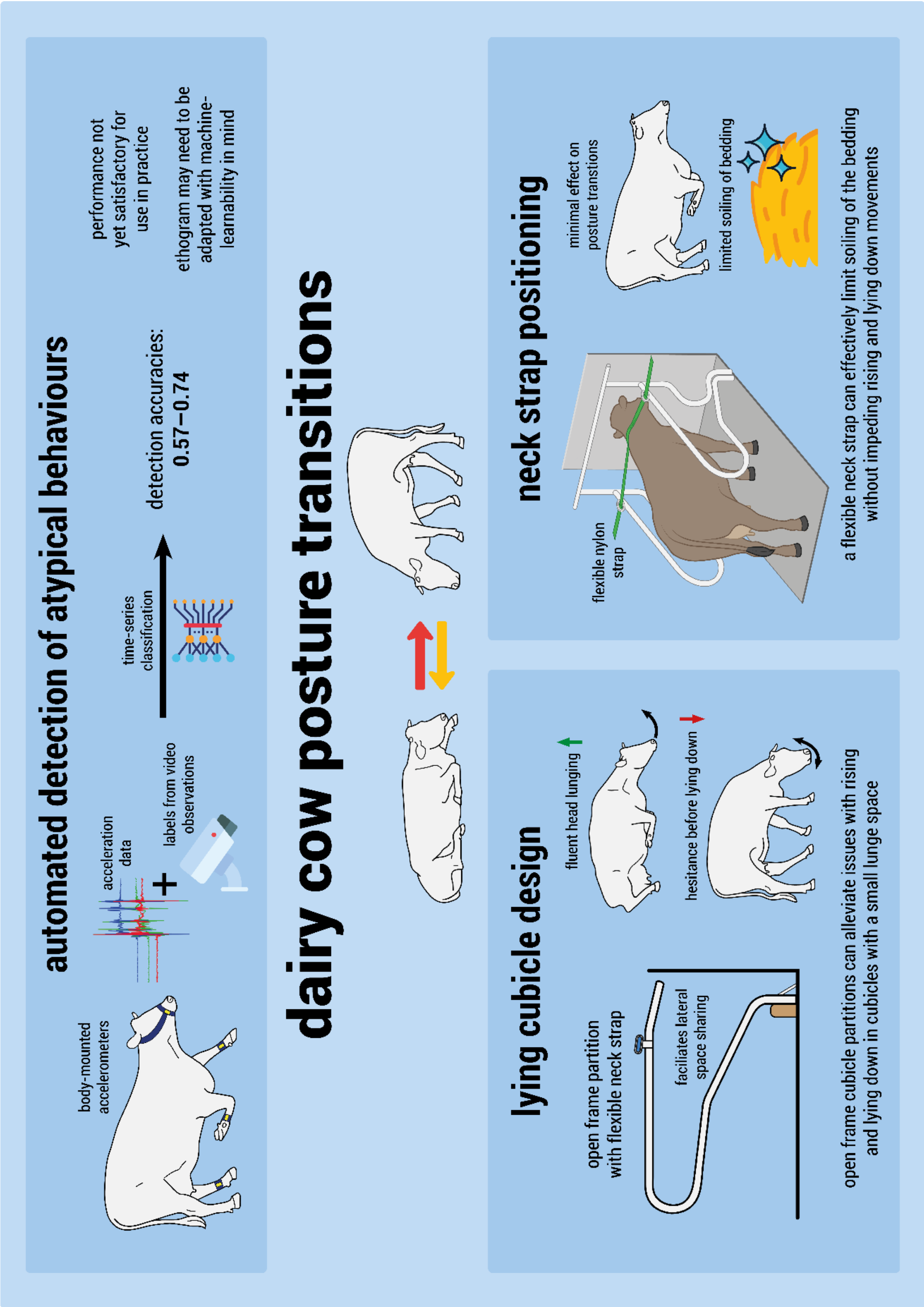
Abstract

In cubicle housing systems for dairy cows, the lying area is divided into individual lying places called lying cubicles. In these cubicles, contamination of the bedding is limited to reduce resource and labour costs and to promote animal hygiene and health. However, lying cubicle design restricts cow behaviour and limits their freedom of movement. This can be particularly problematic as cows rise to the standing position and lie down according to innate, species-specific movement patterns with limited ability to adapt these movements to their environment. Inadequate movement space can result in atypical rising and lying down behaviours and possibly a reduced lying frequency. However, the direct effect of lying cubicle design on rising and lying down movements is a relatively understudied aspect of dairy cow welfare. Therefore, the aim of this thesis was to gain a deeper insight into the effects of lying cubicle design on the rising and lying down behaviours of dairy cows with regard to animal welfare.

Firstly, an automated method to detect specific atypical rising and lying down behaviours in dairy cows was proposed. Cows were fitted with four tri-axial accelerometers attached to both front legs, the left hind leg, and the head. Acceleration time series were matched with presence/absence labels for atypical rising and lying down behaviours from video observations, after which various machine learning algorithms were used for model development. Next, the association between lying cubicle design and the quality of rising and lying down movements was investigated on commercial Swiss dairy farms with small lunge spaces. Farms had either ‘permissive’ lying cubicles with open frame partitions that facilitate lateral space sharing and flexible neck straps, or ‘restrictive’ cubicles with partitions with more bar work and rigid neck rails. The prevalence of atypical rising and lying down behaviours was determined from video recordings. Lastly, the effect of neck strap positioning on rising and lying down behaviours and cubicle hygiene was investigated. Three neck strap heights and two distances from the curb were examined consecutively in an experimental barn with two mirrored pens. Rising and lying down behaviours and elimination behaviour around rising events were analysed from video recordings and cubicle cleanliness was assessed for photographs made at afternoon milking.

Atypical rising and lying down behaviours were detected with balanced accuracies of 0.56 to 0.74. This is not yet satisfactory for use in the evaluation of dairy cow housing systems, but subsequent analysis indicated that performance may improve with more training data. Ethograms designed for human observers are likely suboptimal for machine learning, and adjustments may be needed with machine learnability in mind. In the permissive cubicle type, staggered head lunges and displays of hesitation before lying down were less prevalent, lying frequency was higher and lying time was longer. Soiling of the bedding was limited with flexible neck straps positioned restrictively in terms of recommendations for neck rail placement, while rising and lying down movements or general lying behaviour were not considerably affected. The results suggest that open frame partitions and flexible neck straps can improve the conditions for cows to cope with an atypical environment and promote the expression of natural rising and lying down behaviours, while ensuring the cleanliness and health of the cow.

Graphical Abstract



Zusammenfassung

In Laufställen für Milchkühe ist der Liegebereich in einzelne Liegeboxen unterteilt. In diesen Boxen wird die Verschmutzung der Einstreu limitiert, um Kosten zu reduzieren und die Hygiene und Gesundheit der Tiere zu gewährleisten. Die Gestaltung der Liegeboxen schränkt jedoch die Bewegungsfreiheit der Kühe ein. Dies kann problematisch sein, da Kühe nach angeborenen, artspezifischen Bewegungsmustern aufstehen und abliegen und nur begrenzt in der Lage sind, diese Bewegungen an ihre Umwelt anzupassen. Ein unzureichender Bewegungsraum kann zu atypischem Aufsteh- und Abliegeverhalten und einer verringerten Liegefrequenz führen. Der direkte Einfluss der Gestaltung der Liegeboxen auf das Aufsteh- und Abliegeverhalten ist jedoch relativ wenig untersucht. Ziel dieser Doktorarbeit war es daher, einen tieferen Einblick in die Auswirkungen der Liegeboxengestaltung auf das Aufsteh- und Abliegeverhalten von Milchkühen im Hinblick auf das Tierwohl zu erhalten.

Zuerst wurde ein automatisiertes System zur Erkennung von atypischem Aufstehen und Abliegen bei Milchkühen erarbeitet. Die Kühe wurden mit vier Beschleunigungssensoren ausgestattet, die an beiden Vorderbeinen, am linken Hinterbein und am Kopf angebracht wurden. Die Zeitserien der Beschleunigung wurden mit Labels für die An- und Abwesenheit von atypischem Aufsteh- und Abliegeverhalten aus Videobeobachtungen verknüpft, woraufhin verschiedene Algorithmen des maschinellen Lernens für die Modellentwicklung verwendet wurden. Als Nächstes wurde die Beziehung zwischen der Gestaltung der Liegeboxen und der Qualität der Aufsteh- und Abliegebewegungen auf Schweizer Milchviehbetrieben mit kleinem Kopfraum untersucht. Die Betriebe hatten entweder „grosszügige“ Liegeboxen mit offenen Trennbügeln und flexiblen Nackengurten oder „restriktive“ Liegeboxen mit mehr Gitterwerk an den Trennbügeln und starren Nackenrohren. Die Prävalenz von atypischem Aufsteh- und Abliegeverhalten wurde anhand von Videoaufzeichnungen ermittelt. Schließlich wurde die Auswirkung der Positionierung des Nackengurtes auf das Aufsteh- und Abliegeverhalten sowie auf die Sauberkeit der Liegeboxen untersucht. In einem Versuchsstall mit zwei gespiegelten Buchten wurde nacheinander drei Nackengurthöhen und zwei Abstände zur Streuschwelle untersucht. Das Aufsteh- und Abliegeverhalten sowie das Ausscheidungsverhalten bei Aufstehvorgängen wurden anhand von Videoaufzeichnungen analysiert, und die Sauberkeit der Liegeboxen wurde anhand von beim Abendsmelken erstellten Fotos bewertet.

Atypische Aufsteh- und Abliegeverhalten wurden mit einer *balanced accuracy* von 0,56 bis 0,74 erkannt. Dies ist noch nicht ausreichend für die Bewertung von Stallsystemen, aber die Analyse zeigte, dass sich die Genauigkeit mit mehr Trainingsdaten verbessern könnte. Ethogramme, die für menschliche Beobachter entwickelt wurden, sind wahrscheinlich für maschinelles Lernen nicht optimal. In den grosszügigen Liegeboxen waren stockende Kopfschwünge und Zögern vor dem Hinlegen seltener, die Liegefrequenz war höher und die Liegezeit war länger. Die Verschmutzung der Einstreu war bei restriktiv positionierten Nackengurten limitiert, das Aufsteh- und Abliegeverhalten sowie das allgemeine Liegeverhalten wurden jedoch nicht wesentlich beeinflusst. Die Ergebnisse deuten darauf hin, dass offene Trennbügel und Nackenbänder die Kühe dabei unterstützen können mit einer atypischen Umgebung besser zurechtzukommen, während gleichzeitig das natürliche Aufsteh- und Abliegeverhalten sowie die Sauberkeit und Gesundheit der Kuh gewährleistet werden.

1 Introduction

Cubicle housing (also known as free-stall housing), with varying degrees of pasture access, is the most common housing system for dairy cows in Europe and North America according to the European Food Safety Authority (EFSA, 2023). The cubicle housing system was introduced in the early 1960s to provide cows with greater freedom of movement and more opportunities to express natural behaviours compared to tie stalls, while keeping resource and labour requirements lower than with straw yard housing systems. The latter is achieved by dividing the resting area into individual lying cubicles in which cow behaviour is restricted. In this way, faeces and urine are mainly deposited in the walking alleys, which can be cleaned regularly by manual or automatic manure scrapers or manure robots.

From an animal welfare perspective, lying cubicles should enable cows to cope with an environment that is atypical for them without suffering harm. More specifically, lying cubicles should allow the expression of natural behaviour while ensuring cow cleanliness and health (Bewley et al., 2017). However, these two objectives often collide in cubicle housing, as soiling of the bedding is limited by restricting cow behaviour. Moreover, challenges related to lying cubicle design such as mastitis, lameness, and hoof problems are still common in many modern dairy farms (EFSA, 2023). These health problems are not only detrimental to animal welfare, but can also lead to reduced production and economic losses for farmers.

To address some of these issues, the design of lying cubicles has evolved towards improving lying comfort. However, the direct effect of lying cubicle design on rising and lying down movements is a relatively understudied aspect of dairy cow welfare. Transitioning between standing and lying postures requires larger spatial requirements than stationary standing or lying. Hindrance of rising and lying down movements can elevate injury risks and may discourage resting behaviour (van Eerdenburg and Ruud, 2021). Therefore, ensuring that cows can comfortably rise and lie down is a key aspect of dairy cow welfare in cubicle housing systems. Designing lying cubicles that facilitate natural rising and lying down movements requires an understanding of the natural behaviour of dairy cows.

1.1 The cow and her natural behaviour

Humans domesticated cattle (*Bos taurus*) 8000–10,000 years ago (Caramelli, 2006; Pitt et al., 2019). Selective breeding focused primarily on increasing milk production, but also on docility to ease handling and milking. Despite this, modern day dairy cows still behave and react similarly to their wild-living ancestors. They are highly social animals and synchronise behaviours such as resting and feeding (Stoye et al., 2012; Flury and Gygax, 2016). A herd has a clear dominance hierarchy, which is established through agonistic behaviour such as head butting. Once established, the hierarchy is manifested by subordinate animals displaying avoidance behaviours towards dominant individuals (Kondo and Hurnik, 1990). There are even indications that cows form longer term friendships (Gutmann et al., 2015). The ancestors of domestic cattle were flight animals and a flight response can still be observed in modern day dairy cows. This also means that cows have a heightened sense of their environment and possible escape routes (Ishiwata et al., 2005). In contrast with pigs and poultry, the wild ancestors of domestic cattle, the aurochs, have been extinct for over 300 years (van Vuure, 2005). However, the behaviour of cattle in environments with little human interference can be studied to investigate ‘natural’ dairy cow behaviour.

The activity time budget of cattle is largely dominated by three behaviours: feeding, ruminating and resting (Kilgour, 2012). When housed on pasture, cows spend around 8 h/day grazing. The remainder of the day is largely spent resting while lying down, with daily lying time on pasture being around 9 h/day (reviewed in Tucker et al., 2021). Lying is an important activity for cows, and has a higher priority than feeding and social behaviours (Fisher et al., 2002; Munksgaard et al., 2005). However, there can be a wide individual variation in lying time as it is influenced by a number of factors, including breed, age, weight, lactation stage, oestrus and social status (Sambraus, 1978). Climate conditions can also affect lying times, as cows avoid lying down on wet surfaces and lie down less at temperatures over 30 °C. Lying time is usually divided into 9 to 11 separate periods (bouts) of 60 to 100 min spread out over the day (Tucker et al., 2021). However, the duration of a single bout can vary greatly, with the shortest bouts lasting only a few minutes and the longest bouts lasting up to several hours. The majority of the lying time is spent ruminating, while approximately 4 h/day is spent resting and sleeping (Kilgour, 2012) of which less than an hour is REM sleep (Tucker et al., 2021).

On pasture, cows adopt a number of different lying positions (Figure 1; Schnitzer, 1971). When ruminating, cows typically lie on the sternum and ventral side of the abdomen, with the hind legs folded and the head raised and perpendicular or at a slight angle (<90°) to the body to allow for eructation and swallowing. When resting, cows may lie with their head tucked in, or completely on their side with their hind legs and head stretched (van Erp-van der Kooij et al., 2019). Cows often swing their heads and change the position of their legs while lying in order to relieve the pressure of their body weight on body parts in contact with the ground (Carlsson, 1999). This may involve rising and lying back down on the opposite leg (Huxley, 2006). During sleep, cows lie down with their head supported by their shoulder, allowing their neck muscles to relax. In all lying positions, the cow might have one of her front legs extended forward. On a level surface, cows lie approximately equally on each side. However, some literature suggests a slight preference for the left side by pregnant cows, presumably to reduce pressure of the rumen on other contents of the abdomen (Arave and Walters, 1980; Forsberg et al., 2008; Tucker et al., 2021). On a sloped surface, cows prefer to lie with their heads pointing uphill, which eases rising and lying down (Sambraus, 1971; Webster, 2020). Cows usually lie at least 2 to 3 m apart from each other (Sambraus, 1971).

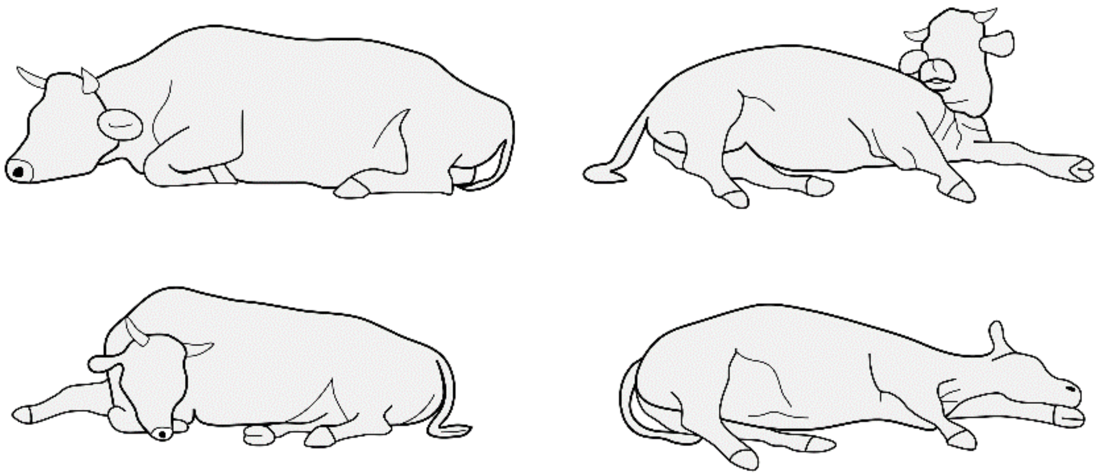


Figure 1. Natural lying positions of cows (reproduced from Schnitzer, 1971).

At the beginning and end of each lying bout, cows need to transition from a standing to a lying posture and vice versa, respectively. Rising and lying down are performed according to species-specific, innate movement patterns (Lidfors, 1989). Rising and lying down are normally continuous and smooth motions, that are constant in shape and similar in animals of different ages and breeds (Kämmer and Tschanz, 1975). Cows have limited ability to adapt rising and lying down behaviours to their environment, as the movements are largely determined by skeletal and muscular structure (Österman and Redbo, 2001). The care and energy involved in rising and lying down movements suggest that they require effort and are not performed casually.

Rising. When rising, the cow first lifts her head, erects her rump and brings her front legs under her sternum, which puts pressure on the sternal region (Figure 2A). With the sternum raised from the ground (Figure 2B), she then thrusts her head forward in the so-called head lunge movement (Figure 2C). Her head bobs downward until her chin touches ground level (Figure 2D). Schnitzer (1971) compared the head lunge movement to a springboard, as the head is used to counterbalance the lifting of the hind legs, while the front knees act as a balancing point (Figure 4). During the head lunge, the cow lifts her hind legs and takes one or more small steps to position them under her body (Figure 2E). At this point, there is considerable strain on the front legs, as approximately two-thirds of the cows' body weight rests on the carpal joints (Metzner, 1976). Cows require approximately one third of their length of forward space for launching their heads (Ceballos et al., 2004), corresponding to approximately 120 to 140 cm measured from the carpal joints (CIGR, 2014). With the head stretched forward, the cow can be more than 3 m long (Lidfors, 1989). Next, the head is retracted, and one of the front legs is straightened and placed forward (Figure 2F). Finally, the other front leg is also straightened (Figure 2G). When rising from the front legs, cows usually take a step forward with the hind legs, so that the cow is standing one step in front of her lying place. Cows usually take a moment to stretch their hind legs with an arched back, before starting to walk forward (Lidfors, 1989; Carlsson, 1999). The whole rising movement takes about 5 to 6 s (Carlsson, 1999; Brouwers et al., 2022).

Lying down. The lying down process can be divided into two phases: the inspection phase, and the lying down movement (Chaplin and Munksgaard, 2001; Österman and Redbo, 2001). Before lying down, cows typically lower their head and position their muzzle close to the ground (Figure 3A). The head is rhythmically swept from side to side in the so-called head pendulum movement to olfactorily inspect the lying area (Figure 3A; Lidfors, 1989). Sometimes, the ground is pawed with one of the front legs (Sambraus, 1971; Brouwers et al., 2022). The duration of the inspection phase can vary, but typically lasts about 10 to 20 s (Carlsson, 1999; Brouwers et al., 2022).

When the lying area is deemed suitable, the cow will position one or both hind legs slightly forward. With the head still lowered, one front leg is bent at the carpal joint (Figure 3B) and placed on the ground (Figure 3C), followed shortly by the other front leg (Figure 3D). She may take one or more small steps with her hind legs away from the intended lying side, bending her body slightly. Next, the hind legs are lowered while the head is stretched forward and used as a counterbalance, and the cow lets herself fall onto the rear flank of the intended lying side (Figure 3E). In this process, the hind leg of the lying side is tucked under the pelvis.

Finally, the cow adjusts her front legs slightly (Figure 3F), to ensure a stable and comfortable resting position (Lidfors, 1989; Carlsson, 1999). The duration of the lying down movement (from the moment one knee touches the ground until the lying down movement is completed) is about 4 to 6 s (Brouwers et al., 2022).

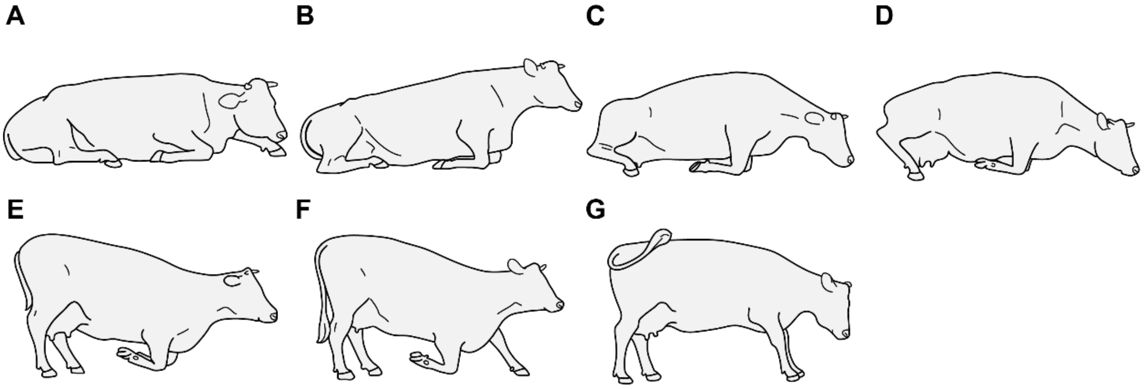


Figure 2. Rising in cattle (reproduced from Schnitzer, 1971).

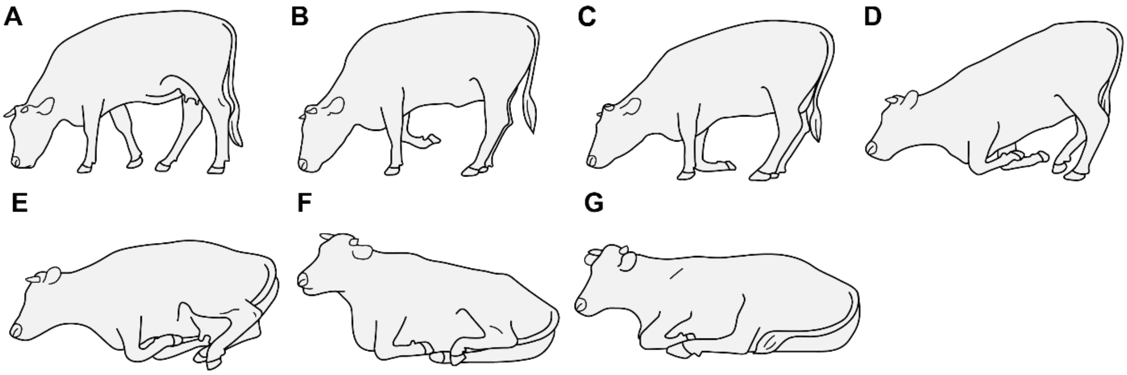


Figure 3. Lying down in cattle (reproduced from Schnitzer, 1971).

1.2 Cubicle housing

Cubicle housing was proposed as a housing system for dairy cows around 1960 (Webster, 2020). The idea behind the cubicle housing system is that cows are not continuously tethered, as they are in tie stalls, but are free to move around the stable, while contamination of the lying area by faeces and urine is limited. This freedom of movement gives cows in cubicle systems more control over their environment, which is known to mediate stress (Englund and Cronin, 2023). Contamination of the lying area is limited by dividing the lying area into individual lying places, so-called lying cubicles, in which cow behaviour is restricted. Specifically, cows are prevented from standing too far forward or sideways in the cubicles so that when a cow defecates or urinates, the likelihood of faeces and urine falling onto the bedding is minimised (Abade et al., 2015). This reduces the cost of providing adequate bedding (Schmisseur et al., 1966; Webster, 2020) and the time required to maintain the cubicle surface (Fregonesi et al., 2009) compared to straw yards. This reduction in resources and labour makes cubicle housing an attractive management system for dairy farmers and cubicle housing is currently the most common dairy housing system in Europe and North America (EFSA, 2023).

1.2.1 Lying area layout

The lying area of a cubicle housing system typically consists of two or more rows of lying cubicles. Ideally, there should be at least as many lying cubicles as there are cows in the stable, so that all animals can lie down at all times. Overstocking leads to competition between cows for lying places, which can result in shorter lying times (Fregonesi et al., 2007) and reduced claw health due to forced standing (Leonard et al., 1996). Cubicle rows may face either a wall (wall-facing cubicles) or another cubicle row (head-to-head cubicles). Cubicle rows are bordered at the rear by walking and feeding alleys where cows can walk freely. These alleys typically have concrete or rubber floors that can be cleaned several times a day by manual or automatic manure scrapers or manure robots (CIGR, 2014).

1.2.2 Lying cubicle design

A typical lying cubicle consists of a lying surface bordered by a curb board at the side of the walking alley and a wall or another lying cubicle at the front (see Section 1.2.1) and is separated from laterally adjacent cubicles by a partition at each side (Figure 4; van Eerdenburg and Ruud, 2021). In the front of the cubicle, the lying area is typically delineated by a brisket board (Carlsson, 1999). The design of lying cubicles should ensure that cows:

- Have a soft, dry and uncontaminated bed to rest comfortably.
- Are able to lie down in natural lying positions, protected from other cows.
- Are able to rise and lie down naturally and comfortably.
- Are able to stand with all four hooves in the lying cubicle, and are not forced to perch (standing with the hind legs in the walking alley) when standing in the cubicle.

Whether or not lying cubicles adequately address these needs depends mainly on the dimensions of the cubicle, the type and quality of bedding, and the type and positioning of cubicle hardware.

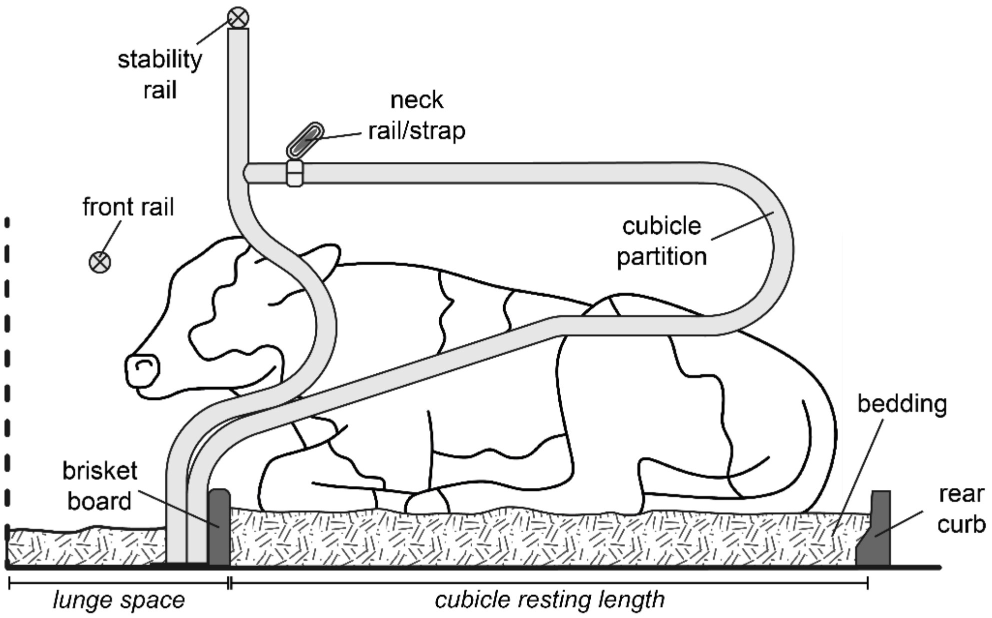


Figure 4. A typical deep-bedded lying cubicle (vector of cow reproduced from dimensions.com). Cubicle partition is of the model *Liberty* (Krieger AG, Switzerland).

1.2.2.1 Lying cubicle dimensions

The space available to cows in the resting area is primarily determined by the dimensions (i.e., the size) of the lying cubicles. The cubicle resting length is defined as the distance from the inside of the rear curb board to the inside of the brisket board (Figure 4). The cubicle width is defined as the distance between the inside of the two cubicle partitions. The lunge space is defined as the space between the cow-side of the brisket board and the wall in wall-facing cubicles. In head-to-head cubicles, the lunge space is not restricted because cows can theoretically lunge next to a cow occupying the opposing cubicle.

Given the increasing size of the modern dairy cow, it is important to relate lying cubicle dimensions to animal size. Cubicle dimensions should be based on the largest 10% of animals in the herd to avoid injuries and discomfort to the larger cows (CIGR, 2014). Commonly used measures of cow size are the height at the withers, the diagonal body length and the width of the chest (Figure 5). The cubicle resting length should be long enough to allow cows to lie comfortably in the cubicle with the udder protected, but not so long that faeces are deposited in the rear of the cubicle. Recommendations for the cubicle resting length range from 1.06 to 1.1 times the diagonal body length (CIGR, 2014; EFSA, 2023). The cubicle width should be wide enough to allow cows to lie down comfortably, but narrow enough to discourage them from turning around and lie down facing the walking alley. A cubicle width of 0.83 times the wither height is recommended (CIGR, 2014; EFSA, 2023). The lunge space can be divided into the space that is taken up by the head of the cow in the resting position and the additional space that is required to lunge the head forward when rising (Bewley et al., 2017). The CIGR (2014) recommends a lunge space of 0.65 times the wither height. In head-to-head cubicles, space sharing can take place between opposing cubicles to gain lunge space.

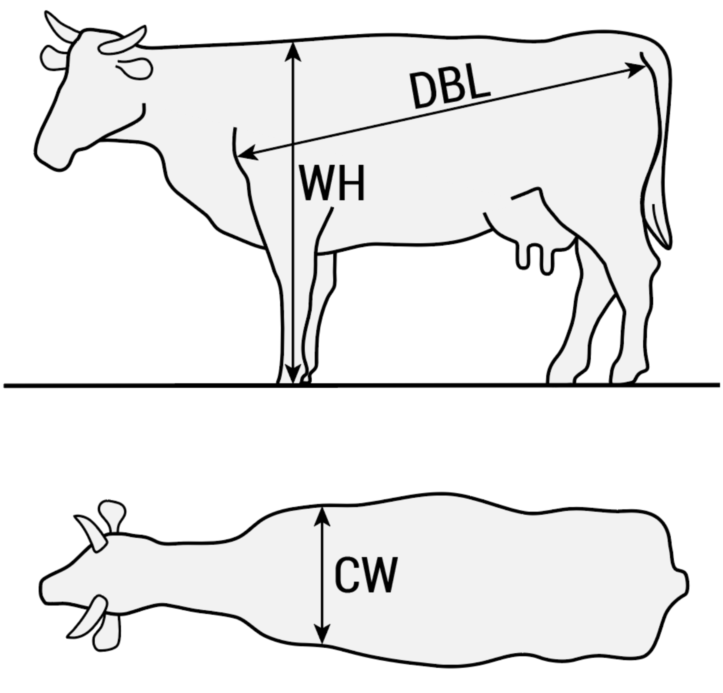


Figure 5. Commonly used body dimensions of cows (reproduced from CIGR, 2014). DBL = diagonal body length, WH = wither height, CW = width at chest.

1.2.2.2 Bedding

Early lying cubicles had a concrete base or compressed earth as only resting surface (Bewley et al., 2017). However, most modern cubicle systems have a compressible lying surface to increase lying comfort. The lying surface should have a sufficient compressibility to adequately conform to the shape of the cow when she is lying down. Lying cubicles can be deep-bedded with loose material such as straw, sawdust, wood chips, sand, hay pellets, and recycled manure solids (van Eerdenburg and Ruud, 2021; EFSA, 2023). The choice of bedding is often related to local availability. In addition to providing lying comfort, important functions of the bedding material are encapsulating faeces and absorbing urine (Tuyttens, 2005). These hygienic properties differ between bedding materials. Field lime can be added to cubicles bedded with straw to create an alkaline environment which inhibits bacterial growth (Mader et al., 2017). Additionally, the mild abrasiveness of the lime may clean manure from legs, flanks and udders. A bedding depth of at least 15 cm should be provided in deep-bedded cubicles (Bickert, 1999). CIGR (2014) recommends that deep-bedded lying cubicles should be maintained (i.e., faecal matter and wet bedding removed and bedding material levelled) twice a day and that clean, dry bedding should be provided at least twice a week.

To reduce the amount of loose bedding and cubicle maintenance required, lying cubicles can also be bedded with cushioning mats or waterbeds fixed to the base of the cubicle. These mats are made of various synthetic materials such as rubber, plastic and foam. This type of cubicle usually has a slightly sloping lying surface and no rear curb. A thin layer of loose bedding material can be added to absorb moisture.

1.2.2.3 Lying cubicle hardware

Lying cubicles are fitted with hardware to guide cows into the cubicles and limit the deposition of faeces and urine on the bedding material. The most important hardware elements are:

Partitions. As mentioned in Section 1.2.2, individual lying cubicles are separated by one another by partitions. Cubicle partitions act as a visual aid to guide the animals into the cubicle parallel to the partitions, and discourage cows from lying down diagonally. In addition, cubicle partitions allow cows to lie closer together than they would in open environments by providing a physical barrier between lying cows (van Eerdenburg and Ruud, 2021). Partitions reduce the possibility of cows disturbing or injuring their neighbours and minimise the risk of limb and teat injuries when cows rise and lie down.

In the first cubicle systems, partitions were made of timber and consisted of two or three horizontal boards supported by two vertical posts embedded in the cubicle base (Figure 6). Not much later, metal rails were used to manufacture cubicle partitions. Over the years, a bewildering variety of lying cubicle partition designs has emerged in response to experience and fashion. Internationally, there are large differences in partition design due to different traditions, legislation, and market requirements (Carlsson, 1999). Partitions may be fixed to a post or can be cantilevered to a wall or to horizontal rails (Figure 6). Early cubicle partition designs focused primarily on stability and durability. Later designs no longer had a rear post to minimise obstruction to cow movements within the cubicles and allow cows to adopt natural lying positions (Veissier et al., 2004). Recently developed partitions also have no support post at the front to facilitate space sharing with neighbouring cubicles, by allowing cows to insert their head and neck through the front of the partition and lunge sideways into the adjacent cubicle (Bickert, 1999; Bewley et al., 2017). Chamfered backs, such as that of the Single Fix partition, enable cows to adopt more natural lying positions because there are fewer lateral restrictions in the hip and pelvic area (van Erp-van der Kooij et al., 2019). Cubicle partitions made of flexible materials, such as plastic, are more permissive to animals than metal partitions due to a lower contact pressure on the cow's body upon collision (Ruud and Bøe, 2011).

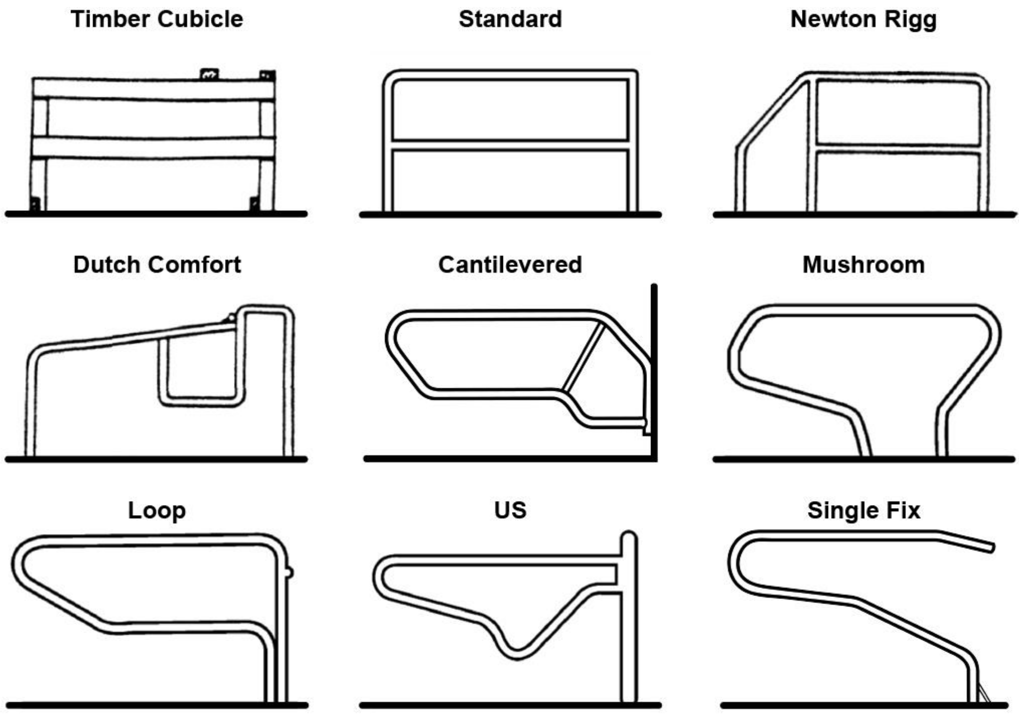


Figure 6. Different designs of lying cubicle partitions for dairy cows (partly reproduced from Loynes, 1985; Veissier et al., 2004).

Neck rail. Typically, a metal bar is placed across the cubicle partitions (Figure 4). This bar, called the neck rail, forces cows to reverse out of the cubicles when they rise and discourages cows from standing too far forward in the resting area to prevent soiling of the bedding material by cows in a standing position. Ideally, cows should be able to stand with all four hooves in the lying cubicle without touching the neck rail and with their rears close to the walking alley to prevent faeces and urine from falling onto the bedding material. Thus, the effectiveness of the neck rail is highly dependent on the correct height and position relative to the rear curb. The CIGR (2014) recommends that the neck rail should be positioned at a height of 0.8 to 0.9 times the wither height. In contrast, the EFSA (2023) recommends that the neck rail should be placed at a height of 0.8 to 0.9 times the diagonal body length. For the distance to the rear curb (vertical plane), the CIGR (2014) advices the cubicle resting length (which they recommend as the diagonal body length times 1.06) + 0.10, whereas the EFSA (2023) recommends 1.2 times the wither height. Nylon straps or chains can be used as a more permissive alternative to metal neck rails (CIGR, 2014; van Eerdenburg and Ruud, 2021). Although certain types of cubicle partitions require the lateral structural support provided by a rigid neck rail (Nordlund and Cook, 2003), this can be overcome by installing a higher rail or a waved neck bar on top of the partitions for stability (Figure 4).

Front rail. In head-to-head cubicles, opposing cubicle rows can be separated by a metal bar, the front rail (sometimes called the head rail), to prevent cows from exiting the lying cubicles at the front (Figure 4; Cook and Nordlund, 2005). As with the neck rail, flexible materials such as nylon straps can also be used to reduce the risk of injury (typically referred to as 'deterrent straps'; Wilson et al., 2022).

Brisket board. As mentioned in Section 1.2.2, the border between the lying area and the lunge space is defined by the brisket board (Figure 4). This board (or tube) aids the cow to position herself in the cubicle when resting or standing and prevents her from lying too far forward in the cubicle (Bewley et al., 2017). The brisket board should be round or without sharp edges to prevent injury to the front legs, and its height should be no more than 10 cm above the surface of the bedding material (van Eerdenburg and Ruud, 2021; EFSA, 2023). The slight slope allows cows to place their legs on the slope during rising, and encourages them to step backwards in the cubicle (Cook, 2019). The brisket board reduces soiling of the bedding material when cows defecate or urinate after rising, but also ensures that cows have some forward space for lunging (CIGR, 2014). Brisket boards can be made out of wood, plastic, rubber, or concrete (van Eerdenburg and Ruud, 2021). A brisket board should allow cows to extend their legs naturally when lying down, which they usually can if the brisket board height is ≤10 cm (Cook, 2019).

Rear curb. The rear curb forms an upwards step that separates the resting area from the manure in the walking alley. In deep-bedded cubicles, the curb also retains the bedding in the cubicle. Curbs can be made out of wood, plastic, rubber, concrete, or metal (van Eerdenburg and Ruud, 2021). The rear curb discourages cows from lying partially in the walking alley with the risk of injury and reduced udder hygiene (CIGR, 2014). The EFSA (2023) recommends a curb height of 15 to 20 cm, without sharp edges, to allow cows to easily enter and exit lying cubicles.

1.3 Risks associated with lying cubicle design

Although cubicle systems are generally considered to be more animal welfare friendly than tie-stalls, cubicle systems have several weaknesses and hazards that can negatively impact dairy cow welfare. A vital aspect of animal welfare is the ability of an animal to cope with and adapt to the demands of its environment (Arndt et al., 2022). However, lying cubicles are designed to minimize soiling of the bedding material, which is primarily achieved by restricting the freedom of movement and limiting cow behaviour within cubicles. Consequently, lying cubicles often do not have the necessary dimensions to allow for natural rising and lying down movements, or cows are hindered by hardware such as partitions and neck rails (Lardy et al., 2021). Hindrance of rising and lying down movements can result in reduced cubicle use, injury and lameness (Veissier et al., 2004). Moreover, being able to rise and lie down without difficulty directly affects the agency of cows, which makes it a primary need for adequate animal welfare. Yet, the direct impact of lying cubicle design on rising and lying down movements is a relatively understudied area of dairy cow welfare.

1.3.1 Atypical rising behaviours

As described in Section 1.1, cows lunge their head forward during rising, for which they use more than 120 cm measured from the carpal joints. However, cows on commercial dairy farms rarely have the lunge space required for a natural, forward-directed head lunge movement (Lardy et al., 2021). Moreover, in head-to-head cubicles where lunge space is shared between opposing cubicle rows, dominant cows may form social obstructions that prevent lower ranked cows from using this space (Cook and Nordlund, 2005). If movement space is restricted, cows are forced to adapt to the available space and will try to counteract the lack of room by modifying their natural movement patterns (Kämmer and Tschanz, 1975; Zambelis et al., 2019). This can result in the prevalence of behaviours that are atypical (i.e., not the norm) under spatially unrestricted conditions, such as on pasture. Moreover, damage to hocks, knees and teats can occur due to collisions with surrounding hardware. Atypical movements during rising can also be caused by harder lying surfaces, such as concrete or insufficient bedding material (Tuyttens, 2005; EFSA, 2023). Therefore, atypical rising behaviours can be used in the evaluation of dairy cow housing systems. The following atypical rising behaviours are described in literature:

Horse-like rising. If virtually no forward space is available (i.e., with severe space restrictions), a cow may raise her forelimbs first instead of the hind limbs. Only then do the hind limbs straighten up to a standing position (Lidfors, 1989; Herlin, 1997). However, the cow may remain in the sitting posture for several minutes before completely rising. The most motion-intensive phase of this movement pattern is the positioning of the two hind limbs (Kämmer and Tschanz, 1975). This movement pattern is described as ‘horse-like rising’, as it is similar to how equid species typically rise from a recumbent posture (Schnitzer, 1971; Zambelis et al., 2019). Horse-like rising has been observed in lying cubicles that were too short, had solid side walls and with slippery floors (reviewed in Lidfors, 1989). Hörning et al. (2000) observed more horse-like rising in traditional lying cubicles compared with straw yards and cubicles with larger dimensions, softer lying surfaces, and less restrictive partitions. Horse-like rising can lead to overloading of the joints and teat damage (Cermak, 1988). Some animals retain this behaviour even when there is no longer any need for it on pasture (Sambraus, 1971).

Interrupted rising movements. If cows are unable or hesitant to rise from their carpal joints, they may interrupt their rising attempt by lowering their hindquarters again after they are lifted from the ground (Dirksen et al., 2020). This may be caused by inadequate positioning of hardware such as the neck rail and the brisket board. Although interrupting the rising movement is also occasionally observed when cows only change their lying side, regular occurrence is considered as abnormal and may be indicative of poor lying cubicle design.

Staggered head lunging. Restricted forward space may prevent cows from performing a smooth head lunge movement. Instead, the head lunge may be characterised by hesitation or staggered movements (Dirksen et al., 2020). The cow may pause briefly, struggle to find balance, or adjust her head and neck position several times before successfully propelling herself forward (Zambelis et al., 2019). This can appear as a forward and backward motion. A cow may abort her attempt to rise after several unsuccessful head lunge attempts. Fernández et al. (2020) showed that cows in cubicles more frequently needed multiple head lunge attempts in order to rise compared to cows housed in straw yards. Cows in traditional cubicles required more head lunge attempts compared with cows in straw yards or cubicles with larger dimensions, softer lying surfaces, and less restrictive partitions (Hörning et al., 2000). Siebenhaar et al. (2012) reported fewer staggered head lunges when switching to a new type of cubicle partition with fewer obstructions in the lateral lunge space. In finishing bulls, the number of rising events with repeated head lunges decreased with increasing cubicle size (Gygax et al., 2005). However, staggered head lunging is also occasionally observed on pasture (Brouwers et al., 2022), suggesting that it is not solely caused by environmental conditions.

Sideways head lunging. If there is not enough lunge space for a forward head lunge, cows may direct their head lunge sideways by bending their neck and/or head to either the left or the right. Whether cows can direct their head lunge to the side depends on whether space sharing with neighbouring cubicles is possible (van Eerdenburg and Ruud, 2021). Many types of partitions contain bar work in the lateral lunge space, obstructing sideways movements (Figure 6). If possible, sideways head lunging may allow cows to perform a smooth head lunge movement in cubicles with a restricted forward space. Hörning et al. (2000) observed more sideways head lunging in traditional lying cubicles compared with cubicles with larger dimensions, softer lying surfaces, and less restrictive partitions. However, sideways lunging is not normal cattle behaviour and may be uncomfortable due to strain and tension on the neck muscles (Kämmer and Tschanz, 1975; CIGR, 2014; Dirksen et al., 2020). Moreover, cows tend to position themselves diagonally in lying cubicles that require sideways head lunging. This in turn can decrease bedding and udder hygiene, as cows that lie diagonally deposit faeces in the rear corners of the lying cubicle (Cook and Nordlund, 2005). Thus, lying cubicle designs that require sideways lunging should be considered at best as compromised situations.

Crawling backwards. A neck rail that is too low can hinder the rising movement and may prevent cows from rising from their front legs because their backs collide with the bar (Bickert, 1999). In this case, cows may need to move themselves backwards while resting on their carpal joints by moving one or both front legs backwards after performing the head lunge (Zambelis et al., 2019; Dirksen et al., 2020). Crawling backwards may cause strain and overloading of the carpal joints, given the pressure of the cow's body weight on the front legs in this posture.

Shifting backwards. In some cases, cows may shift backwards before rising by shuffling around in the lying cubicle to avoid contact with the neck rail and brisket board (Potterton et al., 2011). They may also shift their torso backwards when rising from the carpal joints (Dirksen et al., 2020) because the neck rail prevents them from stepping forward, as they would normally do on pasture. It is not known whether shifting backwards is uncomfortable for cows.

Slipping. If the surface of the lying area is slippery, a cow may slip with her hind legs during rising (Wechsler et al., 2000). Slipping during rising may cause traumatic injuries (Huxley, 2006). To reduce the risk of slipping, Cook and Nordlund (2009) emphasize the importance of a bedding surface that provides some cushion and traction.

In addition to these atypical behaviours, the duration of the rising movement can be used as a general indicator of ease of movement (Österman and Redbo, 2001). The duration of the rising movement can be measured starting from the moment that the cow propels her head forward or sideways until she is standing with all four hooves in contact with the floor in a balanced position. Fernández et al. (2020) observed that the rising duration of cows in cubicle housing was longer than that of cows in straw yards.

1.3.2 Atypical lying down behaviours

Suboptimal lying cubicle design, such as limited movement space and hard lying surfaces, can also cause atypical lying down movements patterns and increase hesitance prior to lying down (Zambelis et al., 2019). Therefore, dairy cow housing systems can also be evaluated using atypical behaviours performed prior to or during the lying down movement. The following atypical lying down behaviours are described in literature:

Dog-sitting. Under severe spatial restrictions, cows may adopt a 'dog-sitting' posture when lying down (Kämmer and Tschanz, 1975). In this case, they first lower their hind legs and take up a sitting position, before lowering their front legs to fully transition to a lying posture (Zambelis et al., 2019). This is essentially the reverse movement pattern of horse-like rising. Similar to horse-like rising, dog-sitting may be harmful to joint health.

Interrupted lying down movements. When cows are hindered or hesitant to lie down, cows may interrupt the lying down movement by placing one or both carpal joints on the ground followed by standing up again (Dirksen et al., 2020). Krohn and Munksgaard (1993) observed more interruptions of lying down in tethered cows on concrete flooring compared to loose housed cows on straw bedding. Müller et al. (1989) frequently observed interruptions of the lying down movement in tethered heifers, but never in loose-housed heifers. Hörning et al. (2000) observed more interruptions of the lying down movement in traditional lying cubicles compared with straw yards and cubicles with larger dimensions, softer lying surfaces, and less restrictive partitions.

Extensive inspection. As described in Section 1.1, inspection of the lying area is part of the natural lying down movement sequence of cattle (Lidfors, 1989). However, the number of head pendulum movements can be used as indicator of how comfortable and familiar a cow is with her environment (Dirksen et al., 2020). In heifers, Müller et al. (1989) observed more investigations of the lying area for tethered compared to loose-housed animals. Dirksen et al. (2020) observed that cows in shorter cubicles performed more head pendulum movements. An increased number of head pendulum movements could be caused by the cow assessing the lying place as suboptimal, but also by previous negative (painful) experiences, such as difficulties during rising or collisions with cubicle hardware. Repeated swinging with the head may also be an expression of frustration, as this behaviour was more frequently observed in cows deprived of lying (Cooper et al., 2007).

Repeated stepping. If a cow is hesitant to lie down, she may also repeatedly shift her weight between her front legs prior to lying down (Dirksen et al., 2020). This behaviour is seldom observed on pasture, and may be performed to test the compressibility of the bedding material, but may also be a general expression of hesitation and may be caused by previous negative experiences. It is also plausible that weight shifting, similar to repeated head swinging, reflects frustration in dairy cows (Cooper et al., 2007). Hörning et al. (2000) observed more repeated stepping with the front legs in traditional lying cubicles compared with cubicles with larger dimensions, softer lying surfaces, and less restrictive partitions or straw yards. Siebenhaar et al. (2012) observed a higher prevalence of repeated stepping with the front legs in cubicles with partitions that restricted lateral space use compared to partitions that facilitated lateral space sharing.

Pawing. On pasture, cattle sometimes paw the ground with their front hooves before lying down (Lidfors, 1989). This behaviour may be performed to test the suitability of the soil for lying (Sambraus, 1971). In cubicle housing, cows are known to paw and lift loose bedding material before lying down when new bedding is provided. Therefore, pawing is not considered as an indication of suboptimal housing per se, but a high degree of pawing could be related to suboptimal lying cubicle design.

Slipping. If the surface of the lying area is slippery, a cow may slip with her front legs when descending onto the carpal joints (Wechsler et al., 2000; Zambelis et al., 2019). As with rising, slipping while lying down can cause traumatic injuries (Huxley, 2006).

As for rising, the duration of the lying down movement can be used in addition to the atypical behaviours described above to assess lying cubicle design. As the lying down process can be divided into two phases, the duration of the inspection phase and the duration of the lying down movement can be recorded separately (Österman and Redbo, 2001). The inspection phase begins when the cow moves her muzzle close to the ground in a pendulum movement and ends when one carpal joint is touching the floor. The lying down movement starts at this moment and ends when the cow is lying in a stable position on either hip. The duration of the inspection phase is mainly indicative of the hesitance of cows to lie down. Interrupting the inspection phase by raising the head may also be an indication of hesitance to lie down. The duration of the lying down movement is indicative of the ease of movement, although the cow has little control over her movement from the moment that she lets herself fall onto her flank. Krohn and Munksgaard (1993) measured increased inspection durations for loose-housed cows compared to cows on pasture, and the longest inspection durations for tethered cows. Cows in cubicles with larger dimensions, softer lying surfaces, and less restrictive partitions needed less time to lie down compared with cows in traditional cubicles or straw yards (Hörning et al., 2000). Wilson et al. (2022) observed a shorter duration of both the inspection phase and the lying down movement in lying cubicles with minimal partitions and no neck rails compared to conventional cubicles. Buchwalder et al. (2000) observed that the duration of lying down movements was prolonged in cubicles with loose straw bedding or conventional rubber mats compared to straw mattrasses and soft mats, respectively. Gieseke et al. (2020) found a negative association between neck rail height and the total duration of the lying down process.

1.3.3 Physical contact with cubicle hardware

Most of the atypical behaviours described above are adaptations of dairy cows to rise and lie down in an unnatural environment. In addition to these potentially harmful behaviours, physical contact with cubicle hardware may cause serious injuries.

1.3.3.1 Collisions with cubicle hardware

Suboptimal design and configuration of lying cubicles can result in cows colliding with the partitions or neck rail when rising, lying down and during lying (Blom et al., 1984; Freinberg et al., 2020). Repeated contact with cubicle hardware can result in abrasions, scratches, bruises, and even bone fractures (Cermak, 1988; Cook and Nordlund, 2005). At slaughter, rib fractures were more common in lame cows compared to non-lame cows, possibly because lame cows had less control when falling onto their rear flank during the lying down movement (Blowey and Bell, 2014). Furthermore, cows in cubicle housing were found to have more hock lesions compared to cows housed in straw yards (Livesey et al., 2002; Fernández et al., 2020). Hörning et al. (2000) found that injuries were more frequent in traditional cubicle systems compared with straw yards or cubicle systems with more permissive lying cubicles. The degree of contact with cubicle partitions during rising and lying down likely depends on the shape of the partition (Siebenhaar et al., 2012). Clean, shiny partitions and neck rails indicate that cows frequently collide with cubicle hardware and that the lying cubicle configuration is not suitable for the herd (Nordlund and Cook, 2003; van Eerdenburg and Ruud, 2021). Cow size is positively associated with the incidence of contact with cubicle hardware (Zambelis et al., 2019). High chances of contact with partitions occur during sideways head lunging during rising, and when the cow falls on her flank during lying down. When rising from the hind legs or carpal joints, the cow may collide with her back or neck against the neck rail.

1.3.3.2 Entrapment

Cows may not only collide with cubicle hardware, but can also become ‘trapped’ in cubicles (Huxley, 2006). This may happen if a cow has to make several head lunges during rising, moving forward slightly with each lunge until her head becomes trapped under or between the bar work of the partition and/or the neck rail (Cook and Nordlund, 2005). In addition, cows may rise with their front legs over the bottom bar of the partition in this is too low, trapping them in the middle of the partition (Cook, 2019). Entrapment can also occur when animals get their hips or legs under the partitions when lying at an angle (Kämmer and Tschanz, 1975). In cases of entrapment, farm staff have to help by pulling the animal’s body back to increase the space in front of the animal, which is likely to be stressful for the cow. Moreover, entrapment can result in traumatic injuries, and, in severe cases, even result in the death of the cow (Webster, 2020). Injuries due to by entrapment appear to have become less common with the developments in cubicle partition design, due to a focus on the positioning of the bar work.

1.3.4 Changes in general lying behaviour

In addition to the effect on rising and lying movements, lying cubicle design is known to influence the general lying behaviour of dairy cows.

1.3.4.1 Lying time

Time spent lying down is commonly used as an indicator of dairy cow welfare (Tucker et al., 2021). Shorter lying times are generally associated with suboptimal lying comfort, such as small lying cubicles and insufficient or wet bedding (Wierenga and Hopster, 1990; Tuyttens, 2005; Reich et al., 2010). Cows housed in straw yards have been found to lay longer than cows in cubicle housing (Fernández et al., 2020). The effect of the type and amount of lying cubicle bedding on lying time has been investigated in several experimental studies (reviewed in Tucker et al., 2021). In general, lying times are longer in cubicles deep-bedded with straw, sawdust or sand than in cubicles covered with rubber mats or mattresses with minimal bedding. This suggests that lying time is related to the comfort of lying surface.

The effects of lying cubicle dimensions and the positioning of cubicle hardware on lying time have been studied less intensively. In tie-stalls, lower lying times were associated with narrow (Bouffard et al., 2017) and short stalls (McPherson and Vasseur, 2021). In cubicle housing, Tucker et al. (2004) also reported shorter lying times in narrow cubicles, but did not find an effect of cubicle length. The height and position of the neck rail relative to the rear curb both had no effect on daily lying time (Tucker et al., 2005; Fregonesi et al., 2009). Ruud and Bøe (2011) observed no difference in lying time between cubicles with fixed or flexible cubicle partitions. Furthermore, the relationship between cow welfare and daily lying time is not always linear, as sick, injured or lame animals may prolong their lying times (Tucker et al., 2021). Nevertheless, deviations from the natural lying times of cows (see Section 1.1) may be an indication of suboptimal lying cubicle design (EFSA, 2023).

1.3.4.2 Lying frequency

Housing conditions may also influence the lying frequency of dairy cows. In tie-stalls, a lower number of lying bouts has been associated with uncomfortable lying surfaces (Haley et al., 2001; Tuyttens, 2005; Rushen et al., 2007) and shorter stalls (Bouffard et al., 2017). Tucker et al. (2009) observed an increase in lying frequency with additional bedding in tie-stalls. Similarly, when comparing lying cubicles with rubber mattresses to cubicles bedded with sawdust and sand, Tucker et al. (2003) reported a decrease of 1.5 and 2 lying bouts per day, respectively. Regarding the positioning of cubicle hardware, Tucker et al. (2005) observed no difference in lying frequency with different neck rail heights. In contrast, Bernardi et al. (2009) reported a lower lying frequency with restrictive neck rail placement. In finishing bulls, the lying frequency increased with enlargement of cubicles (Gygax et al., 2005).

A lower lying frequency means that a cow transitions less often between standing and lying. Thus, reducing the frequency of lying bouts may be an adaptation of cows in response to difficulties and discomfort experienced during rising and lying down (CIGR, 2014), such as pain when resting on the carpal joints due to insufficient compressibility of the bed area or limited forward or lateral space for the head lunge. This is supported by Chaplin and Munksgaard (2001) and Zambelis et al. (2019), who found negative correlations between number of lying bouts and difficulties during rising. Cook and Nordlund (2009) hypothesized that the lower lying frequency with rubber mats is a behavioural response to the difficulty with rising and lying down on flat unyielding surfaces. When rising from rubber mats, there is only a small point of contact between the claw and the bedding surface, increasing the risk of slipping. In contrast, straw and sand provide more cushion and traction, as the claws can dig in the loose bedding, facilitating rising and lying down. Thus, inadequate lying cubicle design likely reduces lying frequency (EFSA, 2023), even though cows should be able to rise easily when needed to relieve discomfort.

1.3.4.3 Mean lying bout duration

The effect of lying cubicle design on mean lying bout duration is less clear. In tie-stalls, mean lying bout durations are typically longer with uncomfortable bedding (Haley et al., 2001; Rushen et al., 2007). However, in cubicle housing, Tucker et al. (2003) observed no apparent differences in mean lying bout duration between cubicles bedded with sawdust, sand or mattresses. Veissier et al. (2004) reported a longer lying bout duration with more restrictive neck rail placement, whereas Tucker et al. (2005) observed no effect of neck rail height on mean lying bout duration. Surprisingly, longer mean lying bout durations have been reported for more spacious tie-stalls (Bouffard et al., 2017; McPherson and Vasseur, 2021). Chaplin and Munksgaard (2001) and Zambelis et al. (2019) both found that lying bout duration was positively correlated with difficulties during rising. This may be to compensate for a reduced lying frequency without compromising daily lying time (Cook, 2019). However, an increased lying bout duration may increase the likelihood of skin damage due to the development of bed sores (Tuyttens, 2005).

1.4 Thesis aim and objectives

Although the risk factors of lying cubicles are reasonably well known, the direct effect of cubicle design on rising and lying down movements is a relatively understudied aspect of dairy cow welfare. Therefore, the aim of this project was to gain a deeper insight in the effects of lying cubicle design on the rising and lying down movements of dairy cows with regard to animal welfare. More specifically, the objectives of this thesis were:

1) To develop an objective and automated method for detecting specific atypical rising and lying down behaviours in dairy cows using accelerometers and machine learning (Appendix I).

2) To investigate associations between lying cubicle design and rising and lying down behaviours of dairy cows in stables with insufficient lunge space (Appendix II).

3) To assess the effect of neck strap positioning on rising and lying down behaviours of dairy cows and lying cubicle hygiene (Appendix III).

2 Materials and Methods

2.1 Study designs

For the development of an automated method to detect atypical rising and lying down behaviours in dairy cows, posture transitions were recorded in a research barn without any modifications to the lying cubicles. Associations between lying cubicle design and rising and lying down behaviours were investigated in an observational study on commercial dairy farms throughout Switzerland. Farms with the 'permissive' cubicle type (n = 4) had open frame partitions and a flexible neck strap, and farms with the 'restrictive' cubicle type (n = 6) had partitions with more bar work in the lateral lunge space and a rigid neck rail. The influence of neck strap positioning on rising and lying down behaviours and cubicle hygiene was investigated experimentally in a research barn with two mirrored compartments. In two subsequent experiments, three neck strap heights (105, 120 and 135 cm) and two distances of the neck strap from the curb (155 and 170 cm) were investigated.

2.2 Animals and housing

A total of 286 lactating dairy cows of the breeds Brown Swiss, Red Holstein, Holstein-Friesian, Swiss Fleckvieh, and their crossbreeds were included in the current work. Of these, 88 cows were housed in the research barns of Agroscope in Aadorf and Ettenhausen, Thurgau, Switzerland. The other 198 animals were housed on 10 commercial dairy farms throughout Switzerland. All cows were housed in cubicle housing systems with deep-bedded lying cubicles.

2.3 Data collection

All cows were fitted with tri-axial accelerometers (MSR 145, MSR Electronics GmbH, Switzerland) attached to the left hind leg. For the development of the automated detection method, additional accelerometers were attached to the head and both front legs of the cows. The triact R package (Simmler and Brouwers, 2024) was used to extract timestamps of rising and lying down events and to calculate measures of general lying behaviour from the data of the accelerometer on the left hind leg. Rising and lying down movements were assessed from video recordings using an ethogram based on Zambelis et al. (2019) and Dirksen et al. (2020; Table 1). This ethogram included rising and lying down behaviours considered as atypical for dairy cows under unrestricted conditions (i.e., on the pasture). When investigating neck strap positioning, the elimination behaviour of the cows shortly before and after rising events and lying cubicle contamination at the afternoon milking were also recorded.

Table 1. Ethogram of atypical behaviors performed during rising and lying down (adapted from Zambelis et al., 2019; Dirksen et al., 2020).

Behavior	Definition
Rising	
Horse-like rising (yes/no)	Cow first raises the forequarters and then the hindquarters.
Interruption (yes/no)	Hindquarters lifted from the ground, but the standing up movement is then terminated by lowering the hindquarters (to the same or other side of the body).
Staggered head lunge (yes/no)	Staggered, interrupted, or repeated motion of the head during the head lunge movement.
Sideways head lunge (yes/no)	Head lunge movement is directed sideways by bending the head and neck to the side.
Crawling backwards (yes/no)	When resting on carpal joints, cow moves her front leg(s) backwards after propelling herself.
Lying down	
Dog-sitting (yes/no)	Cow first lowers the hindquarters and then the forequarters.
Interruption (yes/no)	Carpal joints touch the ground, but the lying down movement is then terminated by raising from the carpal joints.
Extensive inspection (yes/no)	Head lowered and sweeping sideways (while sniffing the bed surface) more than 2 times before the lying down movement.
Repeated stepping (yes/no)	Stepping in place with front legs more than 2 times before the lying down movement.
Pawing (yes/no)	Pawing with front leg just before the lying down movement.

2.4 Data analyses

The automated detection method was developed using a machine learning approach. Time-series around posture transitions were extracted from the combined signal of the different accelerometers and were associated with their corresponding presence/absence labels for the atypical rising and lying down behaviours in Table 1. Different time series classification algorithms were employed for model development using a nested cross-validation strategy. To account for class imbalances, *balanced accuracy* was used as metric for model performance. Differences in performance between classifiers were assessed using Bayesian correlated *t*-tests. To assess whether more data would increase model performance, learning curves were generated by fitting models on subsets of the training dataset of varying sizes.

Associations between lying cubicle design and neck strap positioning on the response variables were investigated using (generalised) linear mixed effects models (Bates et al., 2015). In the analysis of neck strap placement, the position of the neck strap relative to cow body size was used as a continuous explanatory variable. Parametric bootstrapping (10^4 bootstraps) was used to obtain 95% quantile confidence intervals/bands (95% CI) for fixed effects. This is considered to provide a more reliable indication of statistical significance than the p-values based on Wald statistics (Bates et al., 2015). A significant difference from the null hypothesis at the 0.05 level is indicated when the 95% CI does not include the null value (typically 0; 1 for odds ratios).

3 Results

3.1 Automated detection system

Machine learning models detected atypical rising and lying down behaviours to varying degrees. *Crawling backwards* was the best detected atypical behaviour overall, with a balanced accuracy of 0.74 ± 0.02 (mean ± SD). *Staggered head lunge* and *Sideways head lunge* were detected with balanced accuracies of 0.67 ± 0.06 and 0.65 ± 0.06, respectively. *Extensive inspection* was also detected with a balanced accuracy of 0.67 ± 0.06. *Pawing* and *Repeated stepping* were the worst detected atypical behaviours with balanced accuracies of 0.57 ± 0.05 and 0.56 ± 0.05, respectively.

The learning curves for *Crawling backwards* and *Staggered head lunge* did not yet level out with the maximum training data set size. The learning curves for *Sideways head lunge* and *Extensive inspection* plateaued at around 50% of the maximum training dataset size. For *Pawing* and *Repeated stepping*, there was little increase in performance from using 10% of the dataset to using all available training data. Down-sampling of the acceleration data generally decreased detection accuracy. However, only for *Repeated stepping* and *Extensive inspection* did correlated *t*-tests show substantial evidence of a true performance decrease when using data sampled at 10 Hz compared to 20 Hz. For *Staggered head lunge* and *Sideways head lunge* there was no substantial evidence of a true performance decrease even when using a sampling frequency as low as 5 Hz.

For details, see Appendix I (Brouwers et al., 2023).

3.2 Lying cubicle design

Horse-like rising, *Dog-sitting* and *Interrupted* posture transitions were rarely observed in either lying cubicle type. The estimated probability of *Staggered head lunging* was 0.31 higher in the restrictive cubicle type (95% CI: 0.11–0.49) compared to the permissive cubicle type. No associations were found between lying cubicle type and the probability of *Sideways head lunging* or *Crawling backwards*. The estimated probability of *Extensive inspection* was 0.14 higher in the restrictive cubicle type, although with weak statistical support (95% CI: -0.03–0.32). The estimated probability of *Repeated stepping* was 0.19 higher in the restrictive cubicle type, although with weak statistical support (95% CI: 0.00–0.38). No statistical support was found for an association between cubicle type and the probability of *Pawing*.

With the restrictive cubicle type, the estimated daily lying time was 1.9 h/day shorter (95% CI: 0.5–3.4 h/day) and the estimated lying frequency was 1.6 bouts/day lower (95% CI: 0.2–3.1 bouts/day). No statistical support was found for an association between cubicle type and the mean lying bout duration (95% CI: -2–18 min/bout).

For details, see Appendix II (Brouwers et al., 2024).

3.3 Neck strap positioning

Horse-like rising, *Dog-sitting* and *Interrupted* posture transitions were rarely observed with any of the neck strap positions tested. The odds that cows perform *Crawling backwards* during rising decreased by a factor of 0.59 (95% CI: 0.43–0.79) for a 0.1 increase in NSH ratio (neck strap height relative to cow wither height). No statistical support was found for an effect of NSH ratio on the odds that cows perform a *Staggered head lunge* or a *Sideways head lunge* during rising, or on the odds that cows perform *Extensive inspection*, *Repeated stepping* or *Pawing* prior to lying down. No statistical support was found for an effect of NSH ratio on daily lying time, lying frequency or mean lying bout duration. For defecations around rising events, the odds that faeces land in the cubicle increased by a factor of 2.16 (95% CI: 1.47–3.43) for a 0.1 increase in NSH ratio. The estimated probabilities of a cubicle containing faeces at the afternoon milking were 0.19, 0.31, and 0.26 for NSHs of 105, 120, and 135 cm, respectively. Increasing the NSH from 105 to 120 cm increased the probability of a cubicle containing faeces by 0.12, although with weak statistical support (contrast 95% CI: -0.04–0.28). The estimates for the contaminated surface area per cubicle were 126, 226, and 192 cm^2 for NSHs of 105, 120, and 135 cm, respectively. Increasing the NSH from 105 to 120 cm increased the estimated contaminated area per cubicle by 100 cm^2, although with weak statistical support (contrast 95% CI: -20–233 cm^2).

No statistical support was found for an effect of NSD ratio (neck strap distance from the curb relative to cow diagonal body length) on the odds that cows perform any of the investigated atypical rising and lying down behaviours. No statistical support was found for an effect of NSD ratio on daily lying time, lying frequency or mean lying bout duration. For defecations around rising events, the odds that faeces land in the cubicle increased by a factor of 2.44 (95% CI: 1.11–6.07) for a 0.1 increase in NSD ratio. The estimated probabilities of a cubicle containing faeces at the afternoon milking were 0.23 and 0.22, for NSDs of 155 and 170 cm, respectively. The estimates for the contaminated surface area per cubicle were 159 and 184 cm^2 for NSDs of 155 and 170 cm, respectively. No statistical support was found for an effect of NSD on either the probability of a cubicle containing faeces (contrast 95% CI: -0.15–0.13) or the contaminated surface area per cubicle (contrast 95% CI: -175–431 cm^2) at the afternoon milking.

For details, see Appendix III (Brouwers et al., submitted to *Animal*, September 2024)

4 Discussion

In cubicle housing systems, the behaviour of dairy cows is restricted by the design of the cubicles to limit soiling of the bedding material. It is generally assumed that the ability to perform natural behaviours in lying cubicles comes at the expense of cubicle and animal hygiene and vice versa (van Eerdenburg and Ruud, 2021). The relationship between lying cubicle design and dairy cow welfare has been extensively studied, mainly focusing on general lying behaviour (reviewed in Tucker et al., 2021), preferences of cows (e.g., Tucker et al., 2004; Tucker et al., 2005; Abade et al., 2015) and health issues such as lameness (Bernardi et al., 2009) and hock lesions (Cook and Nordlund, 2005; Potterton et al., 2011). However, the relationship between cubicle design and rising and lying down movements has been relatively understudied. These behaviours are performed several times a day according to species-specific, innate movement patterns and cows have limited ability to adapt these movements to their environment (Österman and Redbo, 2001). Furthermore, these behaviours require more movement space than idle standing or lying (Ceballos et al., 2004). The inability to rise and lie down without excessive difficulty directly reduces the cows' agency and their ability to relieve discomfort when lying or standing. As a result, cows may become reluctant to transition between standing and lying and consequently reduce their lying frequency (CIGR, 2014). Therefore, the present work investigated the associations between lying cubicle design and dairy cow rising and lying down behaviours with regard to animal welfare.

A novel method of detecting atypical rising and lying down behaviours using accelerometers and machine learning was proposed. Subsequently, associations between industry innovations in lying cubicle design and dairy cow rising and lying down movements were investigated in commercial and experimental settings. Open frame cubicle partitions with less bar work in the lateral lunge space and flexible neck straps were associated with more fluid head lunges, fewer behaviours indicative of hesitance prior to lying down, a higher lying frequency and a longer daily lying duration. Furthermore, flexible neck straps were effective in limiting soiling of the bedding, but neck strap positioning did not considerably affect rising and lying down movements.

In the following, the method of assessing rising and lying down movements in dairy cows is discussed, and the potential of automated detection methods is further explored. It is also discussed what factors other than the cow's environment may influence posture transitions and what reference should be taken when using rising and lying down movements in the evaluation of dairy cow housing systems. The implications of the findings of the current work for dairy cow housing and welfare are then further elaborated. Lastly, the requirements for innovations in cubicle design that maximise the likelihood of adoption in practice by farmers are considered.

4.1 Method of assessing rising and lying down behaviours

Dairy cow rising and lying down behaviours can be assessed by direct observation in the barn, but this is time consuming and the accuracy of the data may be limited. The availability of camera systems has improved the ability to make direct behavioural observations, as posture transitions can be observed more than once and at slower speeds, but video analysis is still labour intensive. Consequently, rising and lying down behaviours are rarely assessed directly. Instead, many studies measure daily lying duration and lying frequency, and make indirect inferences about the quality of rising and lying down movements (e.g., Bernardi et al., 2009; Fregonesi et al., 2009; Gaworski, 2019). It is likely that measures of general lying behaviour are often used instead of direct assessment of rising and lying down movements for two main reasons. First, general lying behaviour can be determined efficiently and reliably using accelerometers and simple rule-based algorithms (Kok et al., 2015; Simmler and Brouwers, 2024). Second, measures of general lying behaviour are quantitative measures that require less interpretation of behaviour at the stage of data collection than direct observations of rising and lying movements (Vasseur, 2017). This makes measures of general lying behaviour repeatable and less susceptible to subjectivity, as observers are less likely to be influenced by contextual factors. As such, measures of general lying behaviour are relatively straightforward and reliable to record and are therefore often preferred to direct assessments of rising and lying down movements.

However, the total time a cow spends lying per day and the frequency with which she transitions between standing and lying are multifactorial (Tucker et al., 2021). Therefore, changes in lying time or frequency can rarely be attributed to a single aspect of cubicle design. For example, in the current work an increase of almost two hours in daily lying time was observed in cubicles with open frame partitions and flexible neck straps compared to more restrictive cubicles. However, it is plausible that farmers who adopted this permissive cubicle design also implemented broader herd management practices aimed at improving animal welfare or milk production, which may have influenced lying time. It is therefore necessary to directly assess rising and lying down behaviours in order to draw conclusions about the effect of cubicle design on the quality of posture transitions. However, as mentioned above, direct observations are both time consuming and to a certain degree subjective.

4.1.1 Automated detection systems

Automated detection systems have the potential to alleviate the issues of subjectivity and labour-intensive data collection associated with direct observations. The approach of such a system can be divided into two categories: using body-mounted sensors (e.g., accelerometers as investigated in the current work) or using video cameras. Each approach has its own advantages and disadvantages. The main advantage of using body-mounted sensors is that there are no issues with recognising individual animals (as long as it is recorded which sensors are fitted to which animals). In addition, the first step in assessing the quality of posture transitions, the detection of the transitions themselves, can already be achieved with high reliability using existing algorithms for calculating lying frequency (Simmler and Brouwers, 2024). However, attaching sensors to the body is invasive and animals require a period of habituation (MacKay et al., 2012). Furthermore, even after habituation, sensors may affect movement patterns of cows, due to potential discomfort or changes in weight distribution. This can be particularly confounding when looking at detailed behaviours, such as atypical behaviours during rising and lying down. In addition, attaching the sensors is not without risk to the person handling the animals, the sensors are exposed to potential damage, and the sensors may move after attachment, introducing noise into the data. Lastly, the number of information points is limited by the number of sensors attached to each animal, and attaching more sensors increases cost and workload. General behaviours of dairy cows, such as feeding, walking and lying, can reliably be classified using a single body-mounted sensor (Riaboff et al., 2020). However, to detect an atypical behaviour such as repeated stepping with the front legs, at least one sensor may need to be attached to each front leg. To detect all the atypical behaviours described in the introduction, sensors should be placed on almost all independently moving body parts.

By contrast, automatic analysis of videos (i.e., computer vision) is non-invasive and more flexible than using body-mounted sensors. This means that animals do not require a period of habituation and are not hindered by objects attached to their bodies. In addition, instead of being limited by the number of sensors attached to cows, an unlimited number of key points (anatomical landmarks) can be mapped onto an animal's body. This could potentially allow for more detailed analysis of cow movements during rising and lying down. Most work on computer vision models for automated behaviour detection in cows has focused on classifying general behaviours (feeding, lying, walking and standing; Peng et al., 2020; Qiao et al., 2022). However, Kroese et al. (2024) recently showed that rising events can be automatically detected using 3D pose estimation, a technique that uses multiple camera angles of an animal to construct a three-dimensional model of that cow. Although the authors did not use the proposed method to assess the quality of the posture transitions, the data could be matched with labels from human observations to train machine learning models similar to the approach described in the current work. Alternatively, the ease of movement could be assessed by determining the displacement of key points during rising events.

However, a major challenge for computer vision models is the non-contact identification of individual animals (i.e., identification without physically marking the animals). Individual identification is a critical feature for automated detection of atypical rising and lying down behaviours, considering the importance of animal individual factors such as age and body size. In addition, the individual animal needs to be included in statistical models to account for repeated measures. Individual identification of cattle breeds with spotted coat patterns, such as Holstein breeds, may be possible due to individual differences in spotting patterns (Li et al., 2017; Tassinari et al., 2021). However, individual identification of Brown cattle breeds may be more difficult because of their solid coat colours (Gupta et al., 2022). Nevertheless, it is likely that the field of computer vision will achieve satisfactory detection accuracies for the individual identification of cows in the near future, given the overall importance for herd management through early disease detection, better focus on low-ranking animals, and so on.

Lastly, the development of an automated detection system for atypical rising and lying down behaviours, whether using body-mounted sensors or computer vision, may be complicated by the challenge of collecting data on extreme events. For example, horse-like rising was observed only 4 times in the 4262 rising events analysed in the current work, and in 4229 lying down movements, dog-sitting was never observed. The detection of these rare behaviours is highly valuable for dairy cow welfare as they indicate severe difficulties with rising and lying down and are important indicators of poor lying cubicle design (Lidfors, 1989). However, without sufficient training data, machine learning models cannot adequately learn to detect these behaviours. Artificially worsening lying cubicle design in experimental barns to induce difficulties with rising and lying down may not be ethically justifiable. Alternatively, deliberately visiting commercial dairy farms suspected of having poorly designed lying cubicles may be challenging due to the reluctance of farmers to participate.

4.1.2 Ethogram

Findings from the current work also suggest that ethograms for the assessment of rising and lying down behaviours may not be appropriate for machine learning purposes. In other words, the descriptions of the target behaviours are too limited and ambiguous (Siegford et al., 2023). Subjective and relative definitions are ubiquitous in human language. However, using ethograms with definitions of target behaviours that lack precise boundaries will result in poor classification of cases that fall into the grey area. For example, *Sideways head lunge* was defined in the current work as “Head lunge movement is directed sideways by bending the head and neck to the side”. However, this definition does not specify an exact angle at which a head lunge should be labelled as *Sideways*. It may well be that a head lunge angled at e.g., 25° was sometimes labelled as *Straight* and at other times as *Sideways*. This is not only problematic for the development of automated detection systems, but may also reduce intra- and inter-observer reliability. Therefore, whether developing automated detection systems or using direct human observations, there is a need to improve the labelling quality of rising and lying down movements. Possibilities for this may include having multiple human labellers and taking the average of their rating as the likelihood that an atypical behaviour occurred, and revising ethograms to more strictly define the target behaviours.

Furthermore, a detailed and standardised ethogram would improve the comparability of studies on cattle rising and lying down behaviours. Chaplin and Munksgaard (2001) proposed a standardised method for assessing rising behaviours of dairy cows, by assigning each rising behaviour a score of 1 to 5, based on the smoothness of the movement, whether the movement was interrupted, and whether the behaviour was species-specific. More recently, Zambelis et al. (2019) developed a more detailed scoring system using an ethogram that includes specific abnormal behaviours during rising and lying down movements. However, the proposed ethogram does not include all known atypical behaviours (see Introduction), such as repeated stepping with the front legs prior to lying down. Dirksen et al. (2020) used an ethogram based on Zambelis et al. (2019) and included more behaviours, but excluded informative parameters such as slipping and the duration of posture transitions.

The ethograms used in the current work were largely based on Zambelis et al. (2019) and Dirksen et al. (2020). However, these ethograms contain ambiguous language, such as “hesitant motion of the head”. Words such as ‘hesitant’ require a degree of interpretation by the observer, which may come at the expense of inter-observer reliability. Alternatively, a more objective and less ambiguous method of assessing the quality of the head lunge may be to record the number of head lunges required to rise (Gygax et al., 2005; Zambelis et al., 2019). In theory, the durations of the rising and lying down movements provide objective methods for assessing the quality of posture transitions. However, Chaplin and Munksgaard (2001) argue that cows in unfavourable environments may change the pattern of their rising movement but often still take the same time to rise. This is in accordance with findings of the current work, where no difference in rising duration was found between permissive and restrictive cubicle types, despite a difference in the frequency of staggered head lunge movements. In addition, the onset of the inspection phase is not always clear and can be difficult to recognise, particularly on pasture due to its similarity to grazing. Furthermore, cows often interrupt the inspection of the lying area by raising their head, after which they sometimes continue their inspection and at other times search for another lying place. Therefore, an ethogram should clearly define when an inspection is interrupted. Combining textual descriptions with video material could further help to improve the clarity of target behaviours in ethograms and increase inter-observer reliability.

4.1.3 Preference testing

As an alternative to the direct assessment of posture transitions, preference tests are commonly used to evaluate dairy cow lying cubicle design with regard to animal welfare. Preference tests can provide insight into what aspects of housing are important to animals (Dawkins, 2004) and can therefore be used in the design of livestock housing systems (Tucker and Weary, 2001). Using this method, it has been shown that dairy cows prefer rubber mats to concrete floors as a lying surface (Herlin, 1997), lying cubicles without brisket boards to those with brisket boards (Tucker et al., 2006), and flexible cubicle partitions to rigid partitions (Ruud and Bøe, 2011). However, cows often do not show a preference for presumably more permissive lying cubicle designs, such as larger cubicles (Tucker et al., 2004), less restrictive neck rail placement (Tucker et al., 2005; Sudolar et al., 2017), cubicles with minimal partitions (Abade et al., 2015; Wilson et al., 2022), or neck rails covered with foam padding (Gaworski, 2019). Although it is possible that these aspects are not relevant to dairy cows, the results presented in the current work indicate that, for example, partition design is associated with the quality of rising and lying down movements. It is therefore plausible that preference tests with dairy cows may not necessarily reflect what is important for their welfare. Tucker et al. (2004) suggested that cattle may not have the ability or priority to consider the spatial constraints of lying places because they are descended from plain-dwelling animals. For these wild-living ancestors of dairy cows, the quality of the lying surface was probably important, but the assessment of spatial constraints less so, as they were unlikely to lie in confined spaces. This would be consistent with the observed preference of cows for softer lying surfaces (Haley et al., 2001; Rushen et al., 2007).

Furthermore, cattle are myopic and have poor visual acuity (Hulsen, 2005). It is therefore possible that cows may not be able to clearly perceive changes in lying cubicle design, such as a higher neck rail. This means that an animal needs previous experience of rising and lying down in a particular type of lying cubicle and must mentally associate the quality of her posture transitions with the cubicle in order to develop a preference (Fraser and Nicol, 2022). It is unclear whether cattle are able to make this mental association. Lastly, previous housing conditions are also known to influence the preference of dairy cows for aspects of lying cubicle design (Tucker et al., 2003; Wilson et al., 2022). Therefore, preference tests may be less suitable for evaluating lying cubicle design with regard to animal welfare and should ideally be used in combination with direct assessment of rising and lying down behaviour.

4.2 Influence of factors other than environmental

When using rising and lying down behaviours in the evaluation of cattle housing systems, it is important to relate the observations back to those made in unrestricted environments. This will give an indication of the extent to which atypical behaviours are caused by environmental factors, such as the design of the lying cubicle, and other cow-related factors, such as age, body size and breed. For example, the duration of the rising movement has been positively associated with udder volume (Österman and Redbo, 2001), lactation stage (Chaplin and

Munksgaard, 2001), and cow size (Zambelis et al., 2019). Most studies on rising and lying down in dairy cows on pasture were conducted in the 1970s (e.g., Sambraus, 1971; Schnitzer, 1971; Hoffmann and Rist, 1975). However, there has been continuous breeding pressure for high milk production in certain dairy breeds, such as Holstein breeds and Brown Swiss, and milk yield per cow has more than doubled between 1970 and 2010 (Oltenacu and Broom, 2010). As a result, cow body size has increased considerably over the last 50 years. For example, Hoffmann and Rist (1975) used a cow with a wither height of 130 cm as a standard reference cow when comparing posture transitions of cows in tie-stalls with cows on pasture. In contrast, the wither height of the 283 dairy cows included in the statistical analyses of the current work was 149 ± 5.7 cm (mean ± SD) with a range of 133–161 cm. It is plausible that the nearly 15% increase in cow body size has altered the kinematic dynamics of posture transitions, as cows have to displace more weight when rising and lying down. Furthermore, the increase in body size may not have been necessarily proportional, i.e., udder size may have increased more than muscle mass. This would mean that today's cows have to lift more mass with relatively less muscle when rising compared to cows in the 1970s. Österman and Redbo (2001) showed that cows milked three times a day rose faster than cows milked twice a day, presumably due to reduced udder weight. It is therefore possible that today's dairy cows have difficulties with rising and lying down that are inherent to their anatomy and not solely related to their housing conditions.

Therefore, there is a renewed need for studies on the rising and lying down behaviours of dairy cows under unrestricted conditions to put the findings of the current work into perspective and to appropriately use posture transitions in the evaluation of cattle housing systems. These studies should be conducted in a natural environment, such as on pasture, on high yielding breeds under production conditions (i.e., lactating cows) to investigate the effect of udder size and volume on rising and lying down movements. Ideally, study herds should be continuously housed in unrestricted conditions to limit potential confounding factors. For example, cows may have learnt specific movements to cope with inadequate lying cubicle design that have become fixed in their behaviour (Sambraus, 1971), or they may have become hesitant to rise or lie down due to previous negative painful experiences. In addition, cows that have become lame as a result of poor housing conditions are also likely to have problems with rising and lying down on pasture, as lameness is associated with delayed and abnormal rising (Regula et al., 2004; Cook, 2019). Individual characteristics such as wither height, diagonal body length, weight, age and breed need to be recorded so that observations on pasture can be compared with animals of the same proportions and characteristics in cubicle housing.

Lastly, it would be interesting to study the rising and lying down movements of autochthonous cattle breeds to better understand the effect of genetic selection for high milk production on dairy cow posture transitions. Autochthonous cattle breeds have developed and adapted over time to the specific environmental conditions and cultural practices of their area, often through natural processes rather than selective breeding conducted by humans (Felius et al., 2014). For example, Original Braunvieh, the local cattle breed of Switzerland, is closely related to the Brown Swiss breed and originates from the same geographical location (Moscarelli et al., 2021). However, Original Braunvieh has been less influenced by intensive breeding programmes aimed at maximising milk yield. Therefore, comparing posture transitions in unrestricted conditions of Brown Swiss and Original Braunvieh cows may provide valuable insights into the role of intensive selection for high milk yield on dairy cow rising and lying down behaviours. Collectively, the proposed studies would provide a benchmark for interpreting observations on rising and lying down behaviours made in cubicle housing systems.

4.3 Implications of current findings

The relationship between cow comfort and cubicle hygiene has been considered paradoxical, with one generally coming at the expense of the other (Bernardi et al., 2009). However, recent innovations by dairy housing manufacturers investigated in the current work demonstrate that this relationship is not as black and white as is usually assumed. Open frame partitions were associated with more fluid head lunges, suggesting that partitions with less bar work in the lateral lunge space effectively improve conditions for cows to rise in lying cubicles with a small lunge space. In addition, cows showed less signs of hesitance prior to lying down in cubicles with open frame partitions, possibly indicating that they felt more comfortable. Importantly, open frame partitions still fulfil the basic requirements of cubicle partitions, i.e., delineating individual lying places and separating the animals during lying. Therefore, open frame partitions are likely to alleviate problems with rising and improve the welfare of dairy cows, particularly in cubicle housing with a small lunge space. These findings are highly relevant to commercial dairy farming, as they provide farmers with insight into how to improve dairy cow welfare with reasonable investments.

Similarly, nylon straps have been identified as a viable alternative to rigid neck rails, which are considered as a particularly problematic aspect of lying cubicle design due to the high risk of injury and entrapment (Cook and Nordlund, 2005). Given the known problems associated with neck rails, it was rather surprising that flexible neck straps had not been studied scientifically, although they have been commercially available in Switzerland for around 10 years. The current work demonstrates that flexible neck straps can be effective in maintaining proper cubicle hygiene, without considerably impeding rising and lying down movements. These findings are important to commercial dairy farms, which typically struggle to provide lying cubicles that meet the individual needs of cows of different sizes (EFSA, 2023). Innovations such as open frame partitions and flexible neck straps demonstrate that cow comfort in lying cubicles can be improved without compromising cubicle hygiene.

Nevertheless, it is unlikely that dairy cows will ever have complete freedom of movement in lying cubicles and the innovations investigated in the current work still restrict rising and lying down behaviours to some extent. Although open frame partitions may improve conditions for cows to rise in cubicles with a small forward lunge space by facilitating lateral space sharing, cows are forced to lunge sideways instead of being able to perform a natural forward head lunge (Bewley et al., 2017). Lying cubicles with >1 m of forward space would be most optimal for dairy cow welfare. Flexible neck straps are likely to improve the conditions for dairy cows to transition between standing and lying, as collisions cause less abrupt cessation of movement compared to rigid neck rails, but cows are still forced to shift backwards when rising. On pasture, cows typically step forward after rising (Schnitzer, 1971) and observations in the current work indicate that cows in cubicle housing will do so when given the opportunity. Thus, even when lying cubicles are equipped with the latest innovations in terms of animal welfare, cows are still unable to express all of their natural behaviour.

Thus, innovations in lying cubicle design are unlikely to be adopted by farmers if they do not fulfil the original function (usually limiting soiling of the bedding material) of the hardware they replace, even if they are shown to improve dairy cow welfare. Studies on experimental cubicle design can still provide valuable insights into what is important for dairy cows with regard to rising and lying down. However, the industry simply has a greater technical capacity to modify lying cubicle hardware than researchers. In the current work, the company Krieger AG supported the development of adjustable neck strap holders. Joint efforts between researchers and housing manufacturers may be a fruitful way to develop innovative and viable adaptations to lying cubicle design and effectively improve dairy cow welfare in practice.

4.5 Conclusion

The findings of this thesis suggest that the method of assessing dairy cow rising and lying down behaviours should be revised and standardised to improve objectivity, reproducibility, and comparability of future studies. Vague terminology in ethograms should be limited. Automated methods for the detection of atypical rising and lying down behaviours should be further explored, and the greatest potential may lie in computer vision methods. However, both with direct observations and with automated detection methods, ethograms are likely to need improvement. It can also be concluded from the current work that the ability of dairy cows to rise and lie down in lying cubicles can be improved without compromising cubicle hygiene. In cubicles with a small lunge space, open frame cubicle partitions that allow for lateral space sharing with neighbouring cubicles were associated with improved head lunging. Flexible neck straps were identified as a viable alternative to rigid neck rails, as they can effectively limit soiling of the bedding, without impeding dairy cow movements during rising and lying down. Both of these innovations improve the conditions for cows to cope with an environment that is atypical for them and promote the expression of natural rising and lying down behaviours, while ensuring the cleanliness and health of the cow. Animal welfare scientists should continue to work with dairy housing manufacturers to further develop lying cubicles that meet the needs of individual cows, large and small, young and old, dominant and subordinate.

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Appendix I

Brouwers, S. P., Simmler, M., Savary, P., and Scriba, M. F.

2023

Towards a novel method for detecting atypical lying down and standing up behaviors in dairy cows using accelerometers and machine learning

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Abstract

Free-stall cubicles are designed so that cows do not defecate in the bedding material, while still providing comfortable lying places. However, fixed cubicle elements, such as the partition and neck rail, restrict available movement space and may hinder cows from performing natural lying down and standing up movement patterns. Although there are various types of cubicle partitions that differ in shape, dimensions, or materials, there is no method other than visual observations to assess their effects on cow welfare. An automated detection system could improve the efficiency and promote objectivity of such assessments. Therefore, the aim of this research was to explore which atypical lying down and standing up behaviors could be detected using body-mounted accelerometers and machine learning. Three leg- and one head-mounted accelerometer set to record at 20 Hz were fitted to 48 lactating dairy cows (Brown Swiss and Holstein × Swiss Fleckvieh). Lying down and standing up events were simultaneously assessed through video observations, by assigning binary presence/absence labels for atypical behaviors, such as lunging the head sideways when standing up and pawing the bedding material before lying down. Different time series classification algorithms were employed for model development using a nested cross-validation strategy. The best performing classifiers were MiniRocket and the deep learning algorithm InceptionTime. Atypical behaviors performed during standing up events, namely *Hesitant head lunge* and *Crawling backwards*, were identified as most promising candidates for accelerometer-based detection. These behaviors were detected with balanced accuracies of 0.67 and 0.74, respectively, and their learning curves indicated that more training data might further improve model performance. Overall, achieved performances were not yet satisfactory for application in the evaluation of new dairy cow housing installations. Potentially, ethograms designed for human observers are not optimal for machine learning and adjustments with machine learnability in mind might be necessary. The behaviors identified as promising are good candidates for further development into an efficient and objective method that could complement human observations in the assessment of dairy cow housing installations.

1 Introduction

Lying cubicles in free stall systems are designed to provide comfortable lying places for dairy cows while maintaining proper hygiene (Tucker et al., 2005; Fregonesi et al., 2009). Free stall cubicles are separated by partitions and fitted with a neck rail or band above the lying place. These fixed elements prevent cows from standing fully inside stalls and ensure that animals lie down near the end of the stall with their rear towards the walking alley. In these standing and lying positions, cows do not defecate in the bedding material but on the concrete surface of the walking alley which is regularly cleaned by a manure scraper. However, when fixed cubicle elements restrict available space and limit freedom of movement, stall cleanliness may come at the cost of cow welfare (Bernardi et al., 2009).

Limited movement space inside free stall cubicles can specifically hinder cows from performing natural lying down and standing up movements. These posture transitions follow species specific, innate movement patterns in dairy cows (Schnitzer, 1971; Lidfors, 1989). The movements are largely determined by skeletal and muscular structure, leaving cows with limited ability to adapt them to their environment (Österman and Redbo, 2001). The prevalence of specific atypical behaviors during posture transitions, such as lunging the head sideways when standing up and pawing the bedding material before lying down, can indicate inadequate movement space in the lying cubicles (Zambelis et al., 2019; Dirksen et al., 2020). Insufficient space in cubicles combined with other risk factors can cause ulcers, bruises on the metacarpal/metatarsal joints, hock lesions, and lameness (Blom et al., 1984; Weary and Taszkun, 2000; Kester et al., 2014). These health issues can result in economic losses for the farmer because cows might stay in the herd for a shorter time and milk production, fertility, and slaughter value may be reduced (Green et al., 2002; Whay and Shearer, 2017). The breeding selection for a higher milk yield and the associated increase in body size of dairy cows in recent decades have accentuated these issues (Oltenacu and Broom, 2010).

To optimise free stall cubicles both from a hygienic and animal welfare perspective, manufacturers of housing systems have developed various types of cubicle partitions (e.g. Veissier et al., 2004). Assessing the impact of each type of partition on animal welfare is challenging as differences in e.g. shape, dimensions, and materials of the partition have diverse effects on cow behavior. Currently, novel partition types are evaluated through visual analysis of the cows' behavior in the cubicles by a human observer using either direct observations or video recordings. This method is labour intensive and to a certain degree subjective (Vasseur, 2017). Even experienced assessors can be influenced by contextual factors, such as the overall cleanliness of the stall. Thus, there is the need for a method to support assessments made by human observers in the evaluation of free-stall housing installations with regard to cow welfare.

In contrast to visual observations by a human observer, automatic detection systems can provide efficient and objective methods to monitor animal behavior. Sensors, such as accelerometers, are now frequently used to study and monitor cow behavior. From acceleration data, general activities (Martiskainen et al., 2009; Vázquez Diosdado et al., 2015; Riaboff et al., 2020), lying behavior (Finney et al., 2018; Schmeling et al., 2021), grazing and rumination behavior (Rayas-Amor et al., 2017; Reiter et al., 2018; Iqbal et al., 2021), and health problems such as lameness can be tracked (Thorup et al., 2015; Haladjian et al., 2018).

This data gives valuable insight into the welfare and health of animals, and enables farmers, veterinarians, and researchers to make informed decisions (Lovarelli et al., 2020). Similarly, manufacturers of mass produced housing installations and regulatory authorities could evaluate the effects of new products using automatic detection systems (Wechsler, 2005).

Particularly, detecting atypical behaviors performed during posture transitions would be of great value because these are considered informative for decreased cow welfare in a stall-based housing environment (Lidfors, 1989; Zambelis et al., 2019). Lying down and standing up events per se can be detected reliably with leg-mounted accelerometers and rule-based algorithms (Hendriks et al., 2020). However, models for the detection of atypical movements performed during these posture transitions are currently not available. The task of detecting specific atypical movements during these transitions is far more complex than recognising the posture transitions themselves. However, results from human research suggest that it is possible to detect specific characteristics of standing-to-sitting and sitting-to-standing transitions from accelerometer data (Doheny et al., 2013; van Lummel et al., 2013; Lipperts et al., 2017).

In general, supervised classification models are trained to flag events of interest from ‘features’ obtained by selecting and transforming the raw data (O'Leary et al., 2020; Riaboff et al., 2022). Accelerometers collect data in the form of time series, which are often manually transformed into tabular features (e.g. maximum, mean, variance) to be compatible with standard machine learning algorithms. However, recent advances in the field of time series classification (TSC) have provided classifiers that can effectively learn from raw time series data, without the need of manual feature engineering (Bagnall et al., 2017; Ruiz et al., 2021). Many of them are particularly good in exploiting the temporal structure of the data, whereas this information is often poorly preserved when doing manual feature engineering. Therefore, bespoke time series classifiers might be more effective to detect atypical behaviors from accelerometer data than standard machine learning classifiers with manual feature engineering.

The aim of this study was to explore which atypical lying down and standing up behaviors are the most promising candidates to be detected with body-mounted accelerometers and machine learning. For this purpose, eight atypical behaviors described by Zambelis et al. (2019) and Dirksen et al. (2020) were targeted with individual binary classifiers predicting the presence/absence of the behavior. Several recent, conceptually different TSC algorithms, including a deep learning approach, were employed. Additionally, practical aspects of data collection and modelling, such as the effect of accelerometer sampling frequency on classifier performance, were investigated.

2 Methods

Ethical approval for the study was obtained from the Veterinary Office of the Canton Thurgau (Switzerland; TG03/2021, Approval No. 33448).

2.1 Animals and housing conditions

The study was conducted during the summer and autumn of 2021 at the Agroscope research station in Ettenhausen, Switzerland. Data was collected from 48 lactating cows of the two most common dairy breeds in Switzerland (Table 1; 34 Brown Swiss and 14 Holstein × Swiss Fleckvieh). Withers height of the cows was 146.3 ± 4.8 cm (mean ± SD). Cows were selected opportunistically based on availability to participate in the study.

Table 1. Withers height, age, and lactation number (mean and range) of cows summarised per breed.

	Withers height		Age		Lactation number	
Breed	Mean	Range	Mean	Range	Mean	Range
Brown Swiss	145	133–155	5.6	2–13	3.8	1–11
Holstein × Swiss Fleckvieh	148	140–155	4.0	2–6	2.2	1–4

The cows were housed in a free-stall barn that consisted of an exercise yard and three sections, one of which was used in this study. This section consisted of two rows of wall-facing deep-bedded cubicles (eight and nine cubicles, respectively) with a walking alley in between and a feeding alley on the opposite side of the wall of one of the cubicle rows. The cows had constant access to the exercise yard and additionally to the adjacent pasture whenever the weather allowed it. Cubicle partitions were of type *Liberty* (Krieger AG, Ruswil, Switzerland), and more than one cubicle was available per cow. A flexible neck band was installed. Cubicles measured 125 cm in width and 265 cm in length with a brisket board 200 cm from the curb and 65 cm head lunge space (Fig. 1). For the cubicle row adjacent to the feeding alley, a wooden board was removed from the head-facing wall to increase the head lunge space to >65 cm.

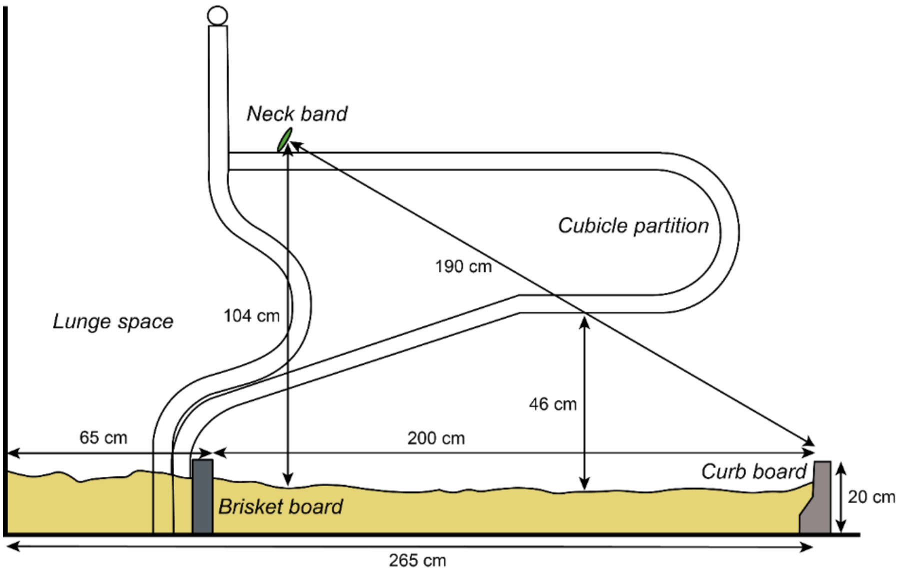

Figure 1. Lying cubicle design and dimensions (partition type *Liberty*, Krieger AG, Ruswil, Switzerland).

Cubicles were maintained twice a day, including removing faeces and levelling of bedding material. The walking and the feeding alley were scraped eight times per day by a manure scraper robot. The cows were milked in a milking parlour twice a day, between 0500 h and 0600 h and between 1600 h and 1700 h, respectively. They were fed a mixed ration twice a day at approximately 0900 h and after the afternoon milking. The mixed ration contained maize, grass, and hay silages, as well as concentrate and minerals. Additional concentrate was offered according to animal-individual allowance in an automated feeding station. Water was available ad libitum from a self-filling water trough.

2.2 Data collection

The complete workflow for data collection, data pre-processing, and model development and evaluation is shown in Fig. 2.

2.2.1 Acceleration data

Acceleration data was recorded along three Cartesian axes (x, y, and z) at ~20 Hz (512 * 26−1 Hz) using MSR 145 data loggers with a tri-axial accelerometer (MSR Electronics GmbH, Seuzach, Switzerland; hereafter referred to as ‘sensors’). Data was stored on the 30 MB internal memory of the sensor. With a sampling frequency of 20 Hz, the battery life of the sensors was longer than a week. The memory capacity was the limiting factor during data collection, since the memory filled up before battery life was depleted. The working range of the accelerometers was ±15 g. Each cow was equipped with four sensors (Fig. 3a): one on the left hind leg (LHL), one on each front leg (RFL and LFL), and one on the left side of the head (H). Sensors LHL, RFL, and LFL were mounted on the outward-facing side of the metatarsus using a piece of foam and self-adhesive bandage (Fig. 3b). Sensor H was placed inside a leather pouch attached to a halter. All sensors were attached when the cows were fixed in the feeding rack during the morning feeding. The recordings started at 0600 h the next morning, giving the cows one day to get used to the sensors and relieve potential stress effects of mounting the sensors. Recordings stopped at 1600 h on the same day, and sensors were removed the next morning, read out, and set up for a new recording. Sensors’ batteries were recharged to full capacity during the data readout. Sensor recordings were made on 22 individual days, each time with 10 cows.

2.2.2 Video data

Two video cameras (Bascom 4XB40K, Bascom, Vianen, The Netherlands) were permanently installed at a height of four metres on opposite sides of the barn so that all cubicles were visible from both cameras. Cameras were connected to a well-accessible recorder (Bascom R4XK, Bascom, Vianen, The Netherlands). Continuous video recordings were made simultaneously to the collection of accelerometer data. The cows were marked with a number on the flank (RAIDEX animal marking spray) to identify individuals from the video footage (Fig. 3a).

Appendix I

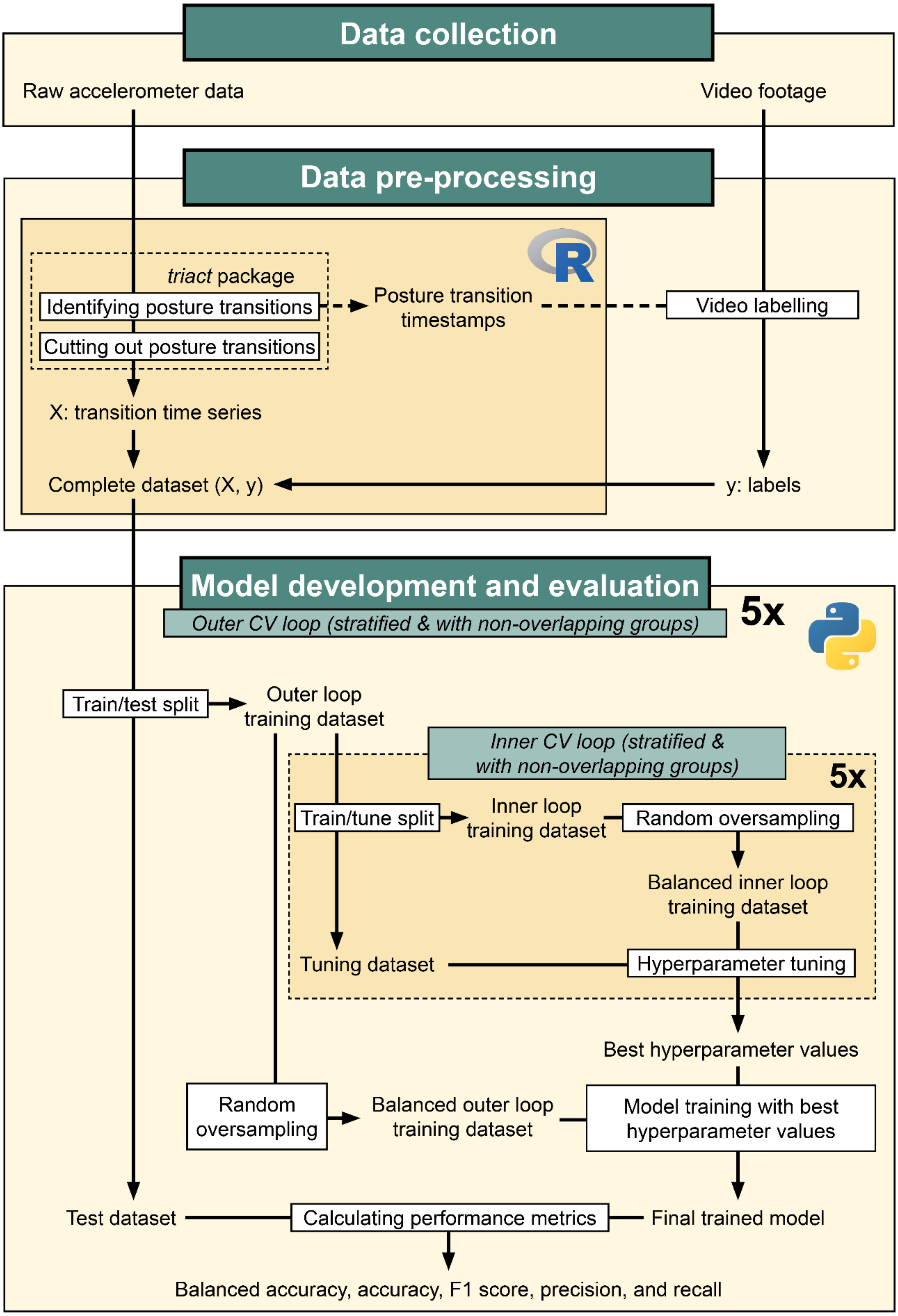

Figure 2. Workflow used to develop classification models for detecting atypical behaviors performed by dairy cows during lying down and standing up events from accelerometer data. CV = cross-validation.

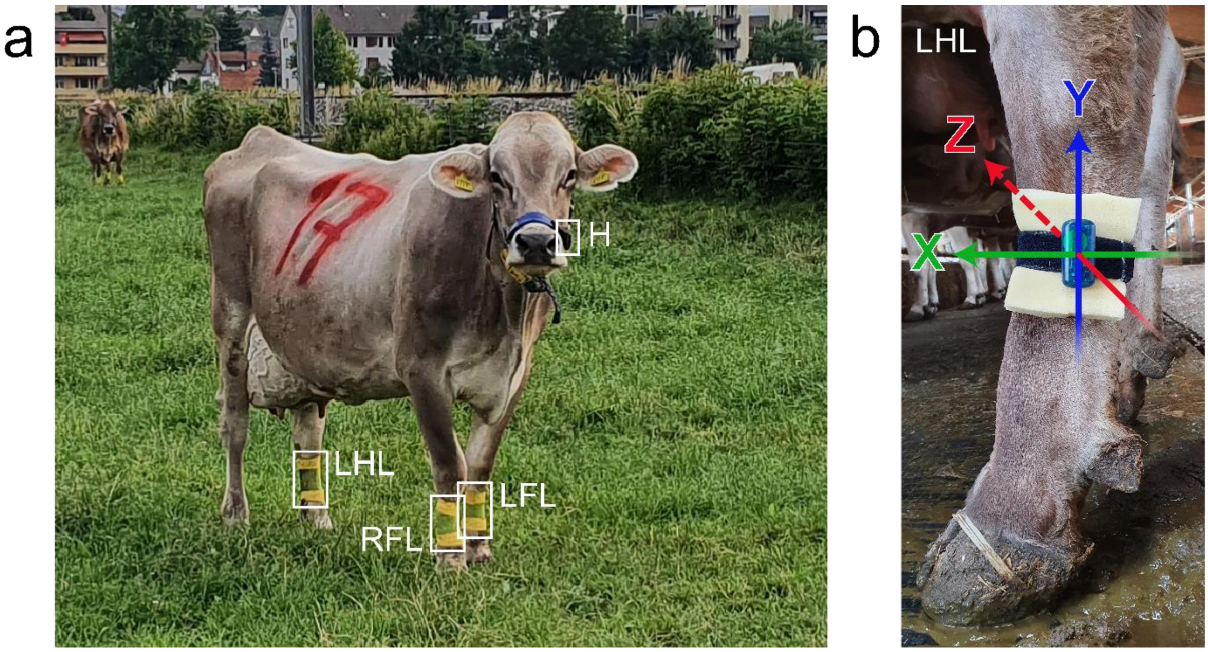

Figure 3. a) Sensors were attached to the left hind leg (LHL) and both front legs (RFL and LFL) with self-adhesive bandage, and to the left side of the head using a halter (H). b) Detailed attachment of sensor LHL and orientation of the recording axes.

2.3 Data pre-processing

2.3.1 Identifying and cutting out posture transitions

Data pre-processing was largely done in R v.4.2.0 (R Core Team, 2023). First, lying down and standing up events were identified from the signal of the accelerometer mounted on the left hind leg using the workflow of the triact R package (v.0.2.0; Simmler and Brouwers, 2023) with default parameters, apart from employing the *add_lying* method with a window size of 25 s for the median filter (window_size = 25) and no minimum lying bout duration (minimum_duration_lying = 0). The triact R package uses a simple rule-based algorithm to differentiate between standing and lying posture based on which axis of the leg-mounted sensor gravitation loads. In total, 560 lying down events and 569 standing up events were identified. The number of lying down and standing up events recorded per cow ranged from 2 to 26 (median: 11) and 2 to 33 (median: 12), respectively.

Based on the maximal duration (87 s) observed in the videos, a time window from 60 s before to 30 s after (90 s in total) the time of posture transition as identified using triact was chosen to cut out lying down events. Standing up events (max. observed duration 54 s) were cut out from 45 s before to 15 s after (60 s in total) the time identified by triact. This resulted in time series lengths of 1772 and 1182 data points for lying down and standing up events, respectively.

2.3.2 Video labelling

Lying down and standing up events in the videos were located using the timestamps obtained with the triact R package (see 2.3.1) and labelled using the scoring system proposed by Zambelis et al. (2019) and the behaviors observed by Dirksen et al. (2020; Table 2). The observer (S.P.B.) had a background in observing animal behavior and was trained by an experienced scientist (P.S.) to assess the specific cow behaviors relevant in this study. To determine intra-observer reliability, the observer scored the same set of 40 videos (20 lying down and 20 standing up movements) once before and once after the video labelling (three months in between). The level of agreement was almost perfect (Cohen's Kappa $\kappa = 0.96$; Landis and Koch, 1977). If a behavior was not clearly identifiable owing to poor video footage (e.g. too dark, too far away from camera), it was not labelled but instead noted as missing value and later excluded from the dataset. The number of observations of each behavior, the class distributions, and the number of different cows that performed the behaviors in each class are given in Table 2. Lorenz curves indicating which percentage of cows performed which proportion of observations in each class are shown in Supp. Fig. 1B and C.

2.4 Model development and performance evaluation

Model development was done in Python 3.7, using the machine learning framework scikit-learn v.1.0.1 (Pedregosa et al., 2011) together with its companion packages imbalanced-learn v.0.9.0 (Lemaître et al., 2017), sktime v.0.8.1 (Löning et al., 2019), and sktime-dl v.0.4.0 (github.com/sktime/sktime-dl). Models were trained via Microsoft Azure Machine Learning Studio on F72s_v2 compute instances, apart from the GPU-based training of InceptionTime, which was conducted on NC4as_T4_v3 compute instances equipped with an NVidia T4 GPU.

The detection of atypical lying down and standing up behaviors from tri-axial accelerometer data can in our case be described as a multivariate times series classification (MTSC) task with n dimensions equal to three (axes) times the number of sensors. Individual MTSC models were developed to detect each atypical behavior. Of the four sensors attached to different body parts, between one and three sensors were used for training the classifiers (Table 2). Sensors were selected based on a preliminary analysis where all possible sensor combinations were systematically tested (MiniRocket models without hyperparameter tuning and balanced accuracy as performance metric). Reducing the number of sensors was intended with regard to the applicability of the proposed automated detection system. Therefore, using a smaller subset of sensors with similar performance was preferred over using a larger subset or all sensors, respectively. For both lying down and standing up, class distributions of *Non-species-specific* and *Interruption* were imbalanced to such an extreme that classifiers could not be fitted for these atypical behaviors (Table 2).

Table 2. Ethogram of atypical behaviors performed by dairy cows during lying down and standing up events (adapted from Zambelis et al., 2019; Dirksen et al., 2020). Number of observations, class distributions, number of different cows that performed the behaviors in the classes, the number of observations that were not clearly identifiable and therefore excluded from the dataset ('NA'), and the sensors selected to detect the behaviors.

Behavior	Definition	No. of observations (distribution in %) [No. of cows]	Selected sensor(s)[1,2]
Lying down			
Non-species-specific (yes/no)[3]	Cow first lowers the hindquarters and then the forequarters ('dog-sitting')	*Yes*: 0 (0%) [0] *No*: 559 (100%) [48] NA: 1 [1]	-
Interruption (yes/no)	Carpal joints touch the ground, but the lying down movement is then interrupted by raising from the carpal joints	*Yes*: 2 (0.4%) [2] *No*: 557 (99.6%) [48] NA: 1 [1]	-
Repeated stepping with front legs (yes/no)	Stepping in place with front legs more than two times before the lying down movement	*Yes*: 61 (11.2%) [24] *No*: 483 (88.8%) [47] NA: 16 [13]	LHL, RFL, LFL
Extensive inspection (yes/no)	Head lowered and sweeping sideways (while sniffing the bed surface) more than two times before the lying down movement	*Yes*: 137 (24.9%) [45] *No*: 414 (75.1%) [48] NA: 9 [6]	H
Pawing (yes/no)	Pawing with front leg (possibly displacing bedding material) before the lying down movement	*Yes*: 47 (8.6%) [20] *No*: 498 (91.4%) [48] NA: 15 [13]	LHL, RFL, LFL
Standing up			
Non-species-specific (yes/no)[4]	Cow first raises the forequarters and then the hindquarters ('horse-like rising')	*Yes*: 1 (0.2%) [1] *No*: 568 (99.8%) [48] NA: 0 [0]	-
Interruption (yes/no)	Hindquarters lifted from the ground, but standing up movement is then interrupted by lowering the hindquarters (to the same or other side of the body)	*Yes*: 2 (0.4%) [2] *No*: 567 (99.6%) [48] NA: 0 [0]	-
Hesitant head lunge (yes/no)	Hesitant, interrupted, or repeated motion of the head during the head lunge movement	*Yes*: 149 (26.2%) [37] No: 419 (73.8%) [45] NA: 1 [1]	LHL, H
Sideways head lunge (yes/no)[5]	Head lunge movement is directed sideways by bending the head and neck to the side	*Right*: 200 (35.5%) [46] *Left*: 185 (32.8%) [44] *Straight*: 179 (31.7%) [43] NA: 5 [5]	LHL, H
Crawling backwards (yes/no)	Backwards movement on carpal joints after the head lunge	*Yes*: 71 (13.0%) [21] *No*: 477 (87.0%) [48] NA: 21 [16]	LHL, RFL, LFL

[1]Dash indicates that no models were developed for the atypical behaviour owing to too imbalanced class distribution
[2]LHL = left hind leg, RFL = right front leg, LFL = left front leg, H = head
[3]In species-specific lying down posture transitions, cows first drop onto their carpal joints and then lower their hindquarters
[4]In species-specific standing up posture transitions, cows first lift their hindquarters during the head lunge and then rise from their carpal joints
[5]Models were trained on the three classes left, right, and straight, and predictions were reclassified to yes (right and left) and no (straight; see Section 2.4.3)

2.4.1 Machine learning models

Three recently proposed MTSC algorithms that are among the best performing algorithms according to common domain-agnostic benchmarks were compared: MiniRocket (Dempster et al., 2021), HIVE-COTE 2.0 (Middlehurst et al., 2021), and InceptionTime (Ismail Fawaz et al., 2020).

MiniRocket is a transform that generates features by transforming the input time series using a large number of convolutional kernels (10^4 kernels). These features are subsequently used to train a linear classifier such as a Ridge regression classifier (Dempster et al., 2021). MiniRocket has a remarkably low computational cost, while achieving high classification performances. HIVE-COTE 2.0 is a meta ensemble classifier that combines four TSC models that use features from different data domains: the shapelet-based Shapelet Transform Classifier, the interval-based Diverse Representation Canonical Interval Forest Classifier, the convolution-based Arsenal (ensemble of Rocket transforms, the predecessor of MiniRocket), and the dictionary-based Temporal Dictionary Ensemble. Each classifier is trained independently and makes a prediction as probability estimate. The probabilities are then combined and weighted by an estimate of the quality of each model to make a final prediction (Middlehurst et al., 2021). HIVE-COTE 2.0 is one of the most accurate TSC models currently available, but its computational costs are excessive. InceptionTime is a recent deep learning model for TSC. It is an ensemble of five deep Convolutional Neural Network models, each with the same architecture but different randomly initialised weights (Ismail Fawaz et al., 2020). Each network is composed of a stack of multiple Inception modules. The core idea of these modules is that multiple filters of varying lengths are applied simultaneously. By stacking several of them, the network is able to extract latent hierarchical features of multiple resolutions (Ismail Fawaz et al., 2020). InceptionTime has been applied to detect arm motor impairment from accelerometer bracelets worn by humans (Wasselius et al., 2021).

In addition to these three recently proposed algorithms, K-Nearest Neighbours with Dynamic Time Warping as distance measure (DTW + KNN) was applied (Berndt and Clifford, 1994). This has long been considered as ‘gold-standard’ and is now a popular TSC benchmark (Ruiz et al., 2021). Lastly, a Dummy classifier that ignores the input and always predicts the majority class in the training dataset was used as a baseline to contrast with the more complex classifiers.

2.4.2 Model development

A nested cross-validation (CV) strategy was used with an outer loop exclusively serving the purpose of evaluating the models’ generalisation performance and an inner loop for hyperparameter tuning (Fig. 2; Wainer and Cawley, 2021). This strategy prevents any leakage of information from the test dataset into the model and thus allows an unbiased estimate of the model’s generalisation performance (Cawley and Talbot, 2010). In the inner CV loop, hyperparameter values (grid search) were evaluated using *stratified group 5-fold* CV. Each individual cow was considered as a group to ensure that data from the same cow were present exclusively in either the training or the tuning dataset. Additionally, the stratification ensured that percentages of observations from each class were preserved in each fold. Because behaviors were imbalanced to different extents, each training dataset was randomly oversampled to equalise the number of observations of the different classes.

Hyperparameter values explored in hyperparameter tuning are listed in Supp. Table 1. Due to its excessive computational cost, HIVE-COTE 2.0 was used with default hyperparameters without tuning. For these models, the inner loop was therefore obsolete and the strategy reduced to non-nested CV. Because behaviors were imbalanced to different extents and all classes were equally important, *balanced accuracy* was used as metric for model performance during tuning as well as during model evaluation (see next section). Balanced accuracy is insensitive to imbalanced class distributions, because it is the arithmetic mean of sensitivity and specificity (Equation 1; Grandini et al., 2020).

$$Balanced\ Accuracy = \frac{sensitivity + specificity}{2} \qquad (1)$$

2.4.3 Performance evaluation

The outer CV loop served the purpose of evaluating model generalisation performance (Fig. 2). As with the inner loop, folds were obtained using *stratified group 5-fold* CV with cows as groups. To ensure unbiased comparison, the same set of folds were used when comparing models. For each outer fold, the model with the best hyperparameter values, as determined in the corresponding inner loop, was fitted to the entire training dataset and evaluated on the test dataset using balanced accuracy, and additionally accuracy, F1 score, precision, and recall. Generalisation performance and model robustness were then determined as mean and standard deviation, respectively, of these metrics across the five outer folds. Model robustness refers to the degree to which performance is affected when changes are made to the training dataset. *Sideways head lunge* was trained on three classes (*straight*, *left*, and *right*; see Table 2), but predictions were reclassified as *yes* or *no*. Preliminary tests revealed that exploiting this additional information on the direction increased performance for the final prediction of the binary labels as compared with using the binary labels for training directly. Finally, differences in performance between classifiers were evaluated using Bayesian correlated t-tests (hereafter simply refererred to as ‘correlated t-tests’; Benavoli et al., 2017) with the *two_on_single* function of the baycomp Python package (v.1.0.2). Only differences of Bayes factor larger than $10^{1/2}$ were considered as substantial evidence for a performance difference between models (Kass and Raftery, 1995; Jeffreys, 1998).

2.5 Effect of training dataset size and accelerometer sampling frequency

MiniRocket was selected for further analysis because it was found to be comparatively well performing and remarkably fast to train. To assess whether more data would increase model performance, learning curves were generated by fitting MiniRocket models on subsets of the training dataset of varying sizes (10% to 100% of the full dataset in 20 steps). Additionally, the trade-off between accelerometer sampling frequency and classifier performance was investigated by fitting MiniRocket models on down-sampled datasets. This trade-off is of interest because a lower sampling frequency implies a lower power consumption and less data to be stored on the device, which in turn eases limitations of memory and battery capacity. The investigated frequencies were 20 Hz (original), 10 Hz, 5 Hz, 1 Hz, and 0.5 Hz. Here too, correlated t-tests were used to compare the generalisation performance of models trained on data with different sampling frequencies. With a sampling frequency of 0.5 Hz, time series approached the minimal length for MiniRocket (nine time points). For both, studying the effect of training dataset size and that of accelerometer sampling frequency, models were fitted according to the outer CV loop as described above (Fig. 2), with hyperparameter values as found to be best for the model developed at 20 Hz with the full dataset (see 2.4.2).

3 Results

3.1 Performance

Best values for hyperparameters as identified in hyperparameter tuning (inner CV loop) are listed in Supp. Table 3. Generalization performances (outer CV loop) as described by balanced accuracies are shown in Fig. 4. All performance metrics (balanced accuracy, accuracy, F1 score, precision, and recall) are listed in Supp. Table 2. Results of correlated t-tests for comparison between the balanced accuracies achieved by the different classifiers are shown in Fig. 5 (comparison of means across folds; Bayes factor > $10^{1/2}$ regarded as substantial evidence for a true difference in performance).

Crawling backwards was the best detected atypical behaviour overall, with a balanced accuracy of 0.74 ± 0.02 (mean ± SD) with InceptionTime (Fig. 4). Correlated t-tests showed substantial evidence for a true difference in performance between InceptionTime and all other classifiers for detecting this behaviour (Fig. 5). *Hesitant head lunge* was detected with a balanced accuracy of 0.67 ± 0.06 using MiniRocket. However, correlated t-tests showed no substantial evidence for a true difference in performance between MiniRocket and HIVE-COTE 2.0 for detecting this behaviour *Extensive inspection* was also detected with a balanced accuracy of 0.67 ± 0.06 using MiniRocket. Correlated t-tests showed substantial evidence that MiniRocket outperformed the other classifiers in detecting this behaviour. *Sideways head lunge* was detected with a balanced accuracy of 0.65 ± 0.06 using InceptionTime. Based on correlated t-tests, there is substantial evidence that InceptionTime performed better than all other classifiers for detecting *Sideways head lunge*. Pawing was detected with a balanced accuracy of 0.57 ± 0.05 by MiniRocket. Correlated t-tests showed substantial evidence that MiniRocket performed better than all other classifiers for detecting this behaviour. Lastly, *Repeated stepping* was the most poorly detected of all behaviours, with a balanced accuracy of 0.56 ± 0.05 achieved with MiniRocket. Correlated t-tests showed no substantial evidence for a true performance difference between DTW + KNN, MiniRocket, and InceptionTime for *Repeated stepping*. For both *Repeated stepping* and Pawing, the performance of all five outer CV folds of the HIVE COTE 2.0 models was the same as that of the Dummy classifier.

Appendix I

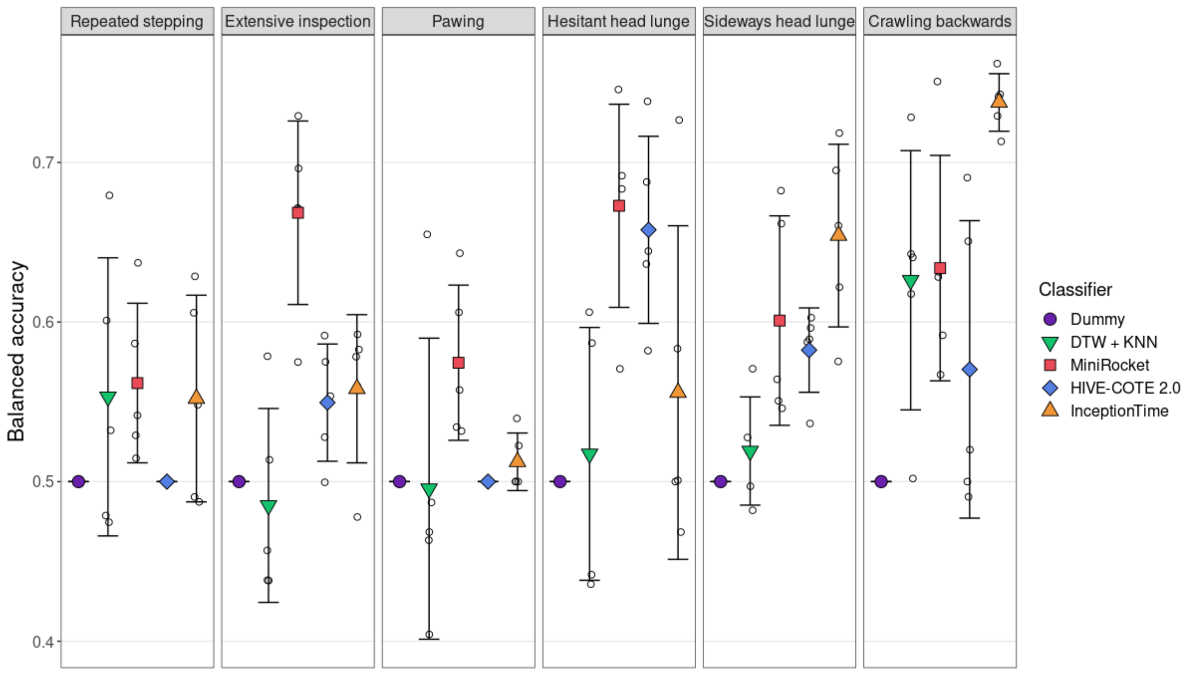

Figure 4. Balanced accuracies (mean ± SD across outer cross-validation folds) in detecting the six atypical behaviours performed by dairy cows during lying down and standing up events with the different classifiers. Open circles show performance observed for the individual outer cross-validation folds. DTW + KNN = K-Nearest Neighbours model with Dynamic Time Warping as distance measure.

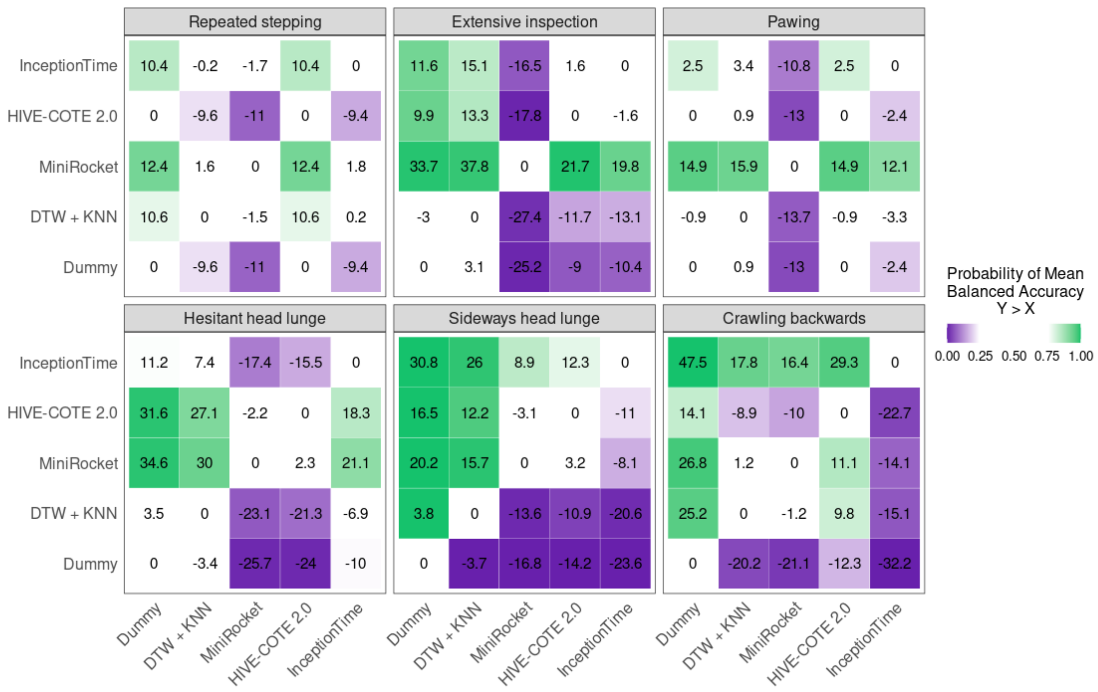

Figure 5. Bayesian correlated t-tests for comparison of classifier performance shown in Fig. 4 (i.e. comparison of the means across the outer cross-validation folds). The colour gradient shows the probability that the classifier on the Y axis outperforms the classifier on the X axis. Probabilities corresponding to substantial evidence for true under- and outperformance (Bayes factor > $10^{1/2}$) are coloured purple and green, respectively. Numbers represent the relative differences (%) in classifier performance with respect to X. DTW + KNN = K-Nearest Neighbours model with Dynamic Time Warping as distance measure.

3.2 Effect of dataset size on performance

The dependency of performance of MiniRocket models on training dataset size is shown for each atypical behaviour in Fig. 6. For *Hesitant head lunge* and *Crawling backwards*, performance increased with increasing training dataset size up to the maximum available dataset size. For *Sideways head lunge*, performance generally increased, but this increase was more erratic. For *Extensive inspection*, Pawing, and *Repeated stepping*, there was little performance increase from using 10% of the dataset to using all available training data.

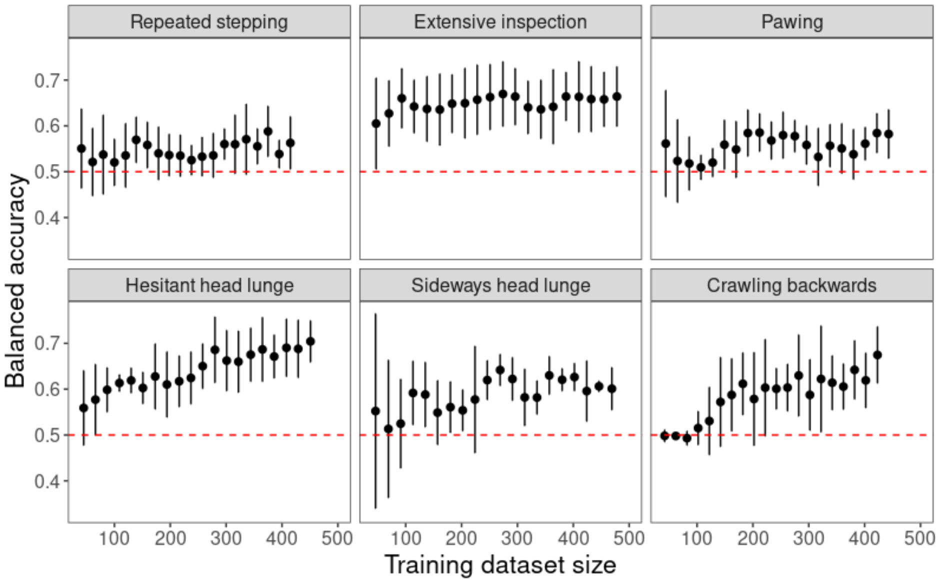

Figure 6. Dependency of performance of MiniRocket models (mean ± SD across cross-validation folds) on training dataset size. Red dashed line indicates performance of the Dummy classifier.

3.3 Effect of accelerometer sampling frequency on performance

Dependency of performance of MiniRocket models on the accelerometer sampling frequency is shown in Fig. 7. The results of correlated t-tests comparing the model performances are shown in Fig. 8, together with the relative differences in performance. In general, lower performance was observed for lower accelerometer sampling frequency. However, correlated t-tests showed only for *Repeated stepping* and *Extensive inspection* substantial evidence for a true performance decrease when using data sampled at 10 Hz as compared with 20 Hz. For *Hesitant head lunge* and *Sideways head lunge*, no substantial evidence for a true performance decrease was found even of when using a sampling frequency of as low as 5 Hz (Fig. 8).

Appendix I

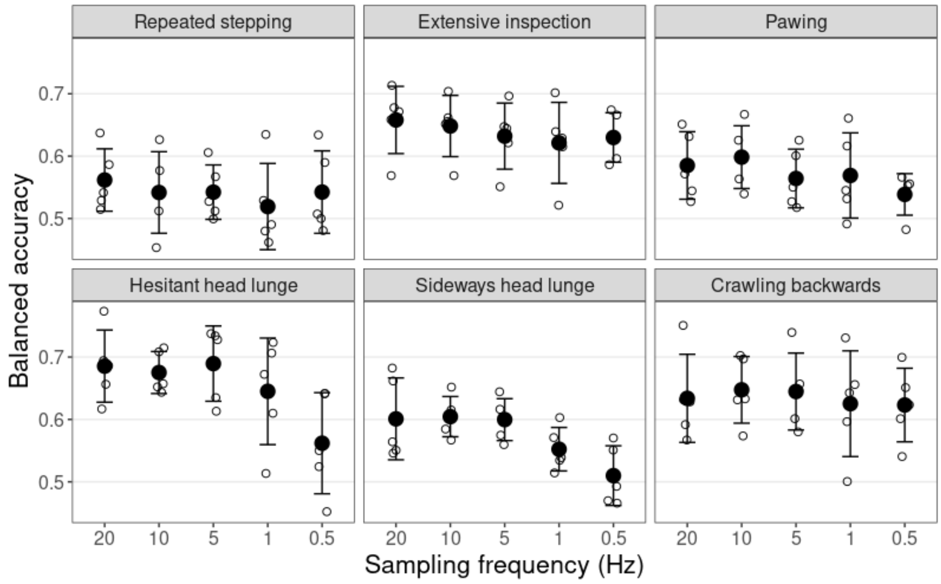

Figure 7. Balanced accuracies (mean ± SD across cross-validation folds) of MiniRocket models trained on accelerometer data with different sampling frequencies. Open circles show the performance observed for the individual cross-validation folds.

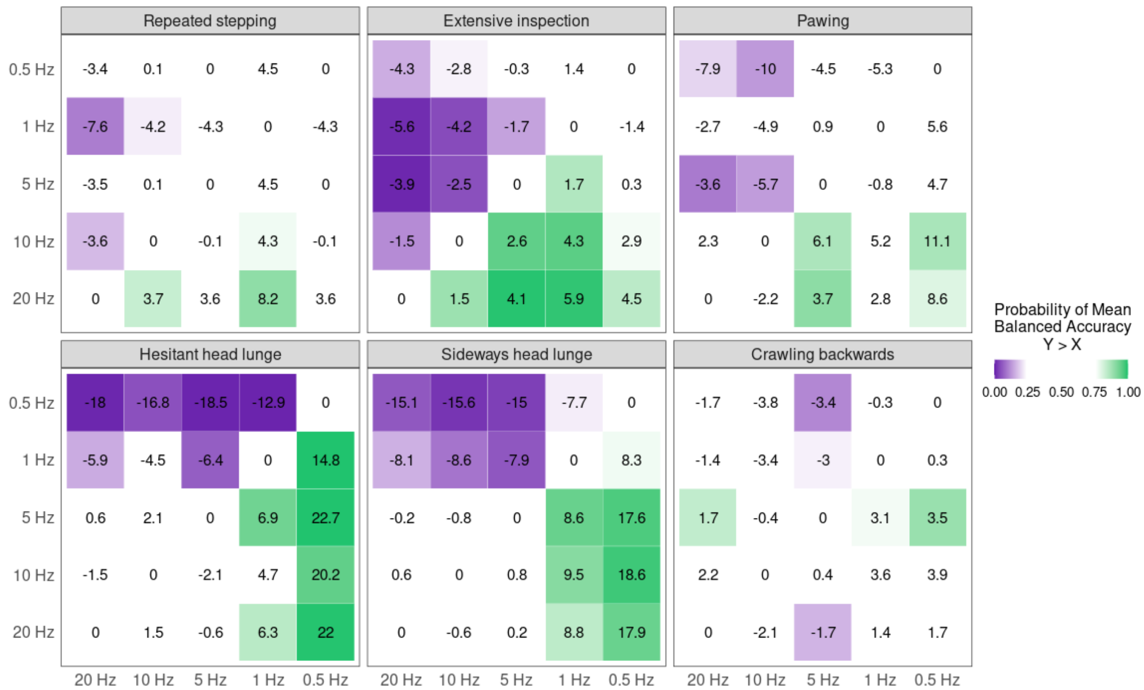

Figure 8. Bayesian correlated t-test comparing performance of MiniRocket models trained on accelerometer data with different sampling frequencies shown in Fig. 7 (i.e. comparison of the means across the cross-validation folds). The colour gradient shows the probability that performances for the frequency on the Y-axis were higher than for the frequency on the X-axis. Probabilities corresponding to substantial evidence (Bayes factor > 101/2) for true under- and outperformance are coloured purple and green, respectively. Numbers represent the relative differences (%) in classifier performance with respect to X.

4 Discussion

The aim of this research was to investigate which atypical behaviours performed by dairy cows during lying down and standing up are promising candidates to be detected using body-mounted accelerometers and machine learning. A two-step approach was used: lying down and standing up events were first cut out of the raw accelerometer data using a reliable rule-based approach. Subsequently, the presence or absence of atypical behaviours was classified using machine learning models based on recent MTSC algorithms.

Achieved balanced accuracies for the detection of the atypical lying down and standing up behaviours ranged from 0.56 ± 0.05 to 0.74 ± 0.02. Best performances were obtained using the MiniRocket time series transform and the deep learning algorithm InceptionTime, which both have not previously been applied to classify time series data from sensors worn by dairy cows. The obtained performances are not yet satisfactory for application in the evaluation of new housing installations with regard to cow welfare. Nonetheless, *Hesitant head lunge* and *Crawling backwards*, appear to be the most promising candidates for accelerometer-based detection. These atypical standing up behaviours were detected with balanced accuracies of 0.67 and 0.74, respectively, and their learning curves indicated that more training data could further increase this performance (Fig. 6).

The two atypical behaviours identified as promising for accelerometer-based detection have the most direct welfare implications for dairy cows. Hesitant head lunges are indicators of inadequate head lunge space, because the available lunge space and the shape of the cubicle partition primarily determine how cows perform the head lunge (Lidfors, 1989). Inability to use the head properly as counterweight directly affects animal welfare by limiting the cow's ability to rise up (Schnitzer, 1971). *Crawling backwards* occurs when cows lie to far forwards in cubicles. It exerts great force on the knee joints, which can result in discomfort and leg injuries (Lidfors, 1989; Wechsler et al., 2000). Because this behaviour is usually caused by inadequate stall dimensions or poor placement of the neck rail, it is highly relevant to farmers and producers of dairy cow housing installations (Hoffman and Rist, 1975).

The prevalence of the poorly detected behaviours, *Repeated stepping* and *Pawing*, is not only related to the design and configuration of fixed cubicle elements, but also to the quality of the lying place. Moreover, these behaviours are mainly indicators of hesitance to lie down and are even occasionally observed on pasture (Lidfors, 1989; Zambelis et al., 2019; Brouwers et al., 2022). Although hesitation does not directly cause physical discomfort or injuries, it could lead to cows lying down less often and for less time (Lidfors, 1989). Therefore, it is still highly relevant to assess indicators of hesitation with regard to dairy cow welfare. *Extensive inspection*, also indicative of hesitance (Krohn and Munksgaard, 1993), was better detected than *Pawing* and *Repeated stepping* and could be a more suitable behaviour to assess hesitation before lying down.

The generally not satisfactory detection performances raise the question whether behaviours as defined in an ethogram designed for human observers are suitable to be detected by machine learning algorithms from accelerometer or other sensor data. For example, *Pawing* is described as pawing the ground with a front leg before the lying down movement (Dirksen et al., 2020). However, this behaviour was also labelled as present when the ground was pawed multiple times within one lying down event, possibly with both front legs. Even though one and multiple occurrences performed with either of the front legs are all evident cases of *Pawing* to a human observer, the variety in actual movements performed by the cow might have prevented the machine learning algorithm from effectively learning the generalisable patterns related to the target behaviour. Surprisingly, *Sideways head lunge* was not among the best detected behaviours. Here, superior model performance was expected compared to detection models for other, seemingly more complex behaviours, such as *Extensive inspection*. This may be due to the lack of a clear boundary between a straight neck and a slightly bent neck in the ethogram (Table 2), which compromised label quality. However, *Sideways head lunge* was better detected when the model was trained on three classes specifying the actual direction of the head movement than when trained on the binary labels (see Table 2). This illustrates that redefining parts of the ethogram may help to increase detection performance for certain atypical behaviours.

In addition, it was occasionally impossible for the human observer to determine the presence or absence of atypical lying down and standing up behaviours beyond doubt. For example, cows occasionally performed multiple head lunge attempts within one standing up event, some of which straight and some directed sideways, leaving the observer puzzled how to record one value for the event. Ambiguous cases like these introduce a degree of error in the labels. Again, redefining the ethogram might alleviate the problem – classifying behaviours in more detail, for example with additional categories, could improve the quality of the labels and model performance.

Differences in class imbalance might partly explain why some atypical behaviours were better detected than others. The least well detected behaviours, *Repeated stepping* and *Pawing*, were the least often performed ones, with class distributions being around 1:10 (presence:absence, Table 2). This imbalance in combination with a limited amount of data leaves only few instances of the presence class for the machine-learning models to learn generalisable patterns in the data related to the behaviour. The random oversampling used in the study (Fig. 2) does not discard any potentially useful information from the already limited dataset (as opposed to random undersampling). However, as it balances the class distribution by duplicating instances from the minority class, it may lead to overfitting if there are very few observations of the minority class (Menardi and Torelli, 2014).

Additionally, there were large inter-individual differences in class balances between cows. For example, *Pawing* and *Repeated stepping* were never performed by approximately half of the cows included in the study, whereas other individuals performed these behaviours often (Supp. Fig. 1B). These differences could have caused the machine-learning models to learn patterns specific to the individual cows and not related to the behaviour in a generalisable manner. Consistent with this rationale, for the better-detected behaviours related to the head lunge, inter-individual distribution was more favourable because at least 75% of all cows performed these behaviours at least once. However, the best-detected behaviour overall, *Crawling backwards*, had the largest inter-individual imbalances (Supp. Fig. 1B).

Substantially more data and employing random undersampling to balance class distributions, potentially even per cow, could improve detection performance. A sound strategy would be to collect more data on different farms (with different cubicle partitions and dimensions), where the atypical behaviours may be more common than in the research barn in this study.

In the further development of this method, the sampling frequency of the sensors could likely be reduced, saving battery life and storage capacity, without substantially sacrificing model performance. Subsampling the time series data from 20 Hz to 5 Hz did not decrease the performance of MiniRocket models for the identified most promising behaviours, *Hesitant head lunge* and *Crawling backwards*. Moreover, for behaviours where lowering the sampling frequency to 10 Hz negatively affected performance, it decreased only by 4% as compared with 20 Hz.

5 Conclusion

A novel method was investigated to detect atypical lying down and standing up behaviours in dairy cows using accelerometers and machine learning. Overall, achieved detection performances for the atypical lying down and standing up behaviours were not yet satisfactory for application in the evaluation of new housing installations with regard to cow welfare. However, two behaviours associated with a hindered standing up movement were identified as promising candidates for accelerometer-based detection using machine learning. *Hesitant head lunge* and *Crawling backwards* were detected by balanced accuracies of 0.67 and 0.74, respectively, and their learning curves indicated that more training data might further increase model performance. Therefore, these behaviours should be considered in the further development of an accelerometer-based method to assess standing up behaviours of dairy cows. The generally rather poor detection performance of atypical lying down behaviours might indicate that behaviours, as described in an ethogram designed for human observers, might often not be suitable for detection by machine learning. Detection performances may be improved by adjusting the ethogram with machine learnability in mind. Issues with imbalanced class distributions and inter-individual differences could potentially be alleviated by collecting substantially more data in stables with different lying cubicles. When developed further, the proposed method could improve efficiency and promote objectivity in the evaluation procedure of dairy cow housing installations by complementing human observations.

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Appendix II

Brouwers, S. P., Simmler, M., Scriba, M. F., and Savary P.

2024

Cubicle design and dairy cow rising and lying down behaviours in free-stalls with insufficient lunge space

Animal 101314

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Abstract

Cubicle partitions divide the resting area of free-stalls into individual lying places for cows, thereby facilitating the maintenance of good hygiene and reducing competition by separating animals. The forward lunge space in lying cubicles is often insufficient for a natural head lunge movement during rising. Cubicles with open frame partitions and a flexible neck strap aim to alleviate this welfare issue. The open partition frame facilitates lateral space sharing (using space of neighbouring cubicles for the head lunge movement) and the flexible neck strap is presumably less painful upon collision. In an observational study, we investigated the lying behaviour of free-stall housed dairy cows in this 'permissive' cubicle type with open frame partitions and a flexible neck strap positioned relatively high above the lying surface compared to 'restrictive' cubicles with partitions with more bar work in the lateral lunge space and a lower-positioned rigid neck rail. The study was conducted on commercial Swiss dairy farms with exclusively wall-facing lying cubicles of either the permissive (4 farms) or restrictive (6 farms) type. The forward lunge space on these farms ranged from 55 to 70 cm, which we considered insufficient for adult cows to lunge their heads forward. On each farm, 18–20 lactating dairy cows were selected. In total, 188 animals were used in the statistical analysis. Over 1.5 days, rising and lying down movements were videotaped, and the prevalence of atypical behaviours during these movements was recorded. In addition, we determined the daily lying duration, the lying frequency, and the mean lying bout duration using accelerometers mounted on the left hind leg. The data was analysed in relation to the cubicle type (permissive or restrictive). In the permissive cubicle type, staggered head lunge movements during rising and displays of hesitance before lying down were less prevalent. The lying frequency was higher and daily lying duration was longer in the permissive cubicle type, although these estimates should be interpreted with caution due to the short data collection period. The results of this study suggest that the permissive cubicle with open partitions and a high-positioned flexible neck strap may improve conditions for dairy cows to rise and lie down. A permissive cubicle design may therefore improve cow welfare in free-stalls with insufficient forward lunge space, where increasing lunge space is not feasible.

1 Introduction

In free-stall housing systems for dairy cows, the resting area is divided into individual lying places by cubicle partitions. Together with a transverse neck rail, these partitions guide cows into the lying cubicle and ensure that they lie down near the end of the cubicle with their rears toward the walking alley. This promotes defecation and urination in the walking alley, and increases the hygiene of the lying area (Abade et al., 2015). Additionally, cubicle partitions help prevent undesirable behaviours, such as diagonal lying and turning around, while allowing cows to lie closer together than they would in open environments by providing a physical barrier between lying cows (van Eerdenburg and Ruud, 2021).

However, cubicle partitions and the neck rail can restrict the movement of cows during rising and lying down. This is particularly problematic because cows rise to the standing position and lie down according to innate, species-specific movement patterns with limited ability to adapt these movements to their environment (Lidfors, 1989; Österman and Redbo, 2001). During rising, a cow normally thrusts her head forward, the so-called head lunge movement, and uses it as a counterweight to generate the momentum needed to stand up (Lidfors, 1989). On pasture, cows use 1.20 m to 1.40 m of forward space for this movement (measured from the front of the carpal joints; CIGR, 2014). In free-stalls, the available forward space is determined by the size of the head space plus lunging space, hereafter together referred to as 'lunge space' and defined as the distance from the cow side of the brisket board to the wall in wall-facing cubicles or to an opposing cow in head-to-head cubicles. On commercial dairy farms, cows rarely have the >1 m of lunge space required for a natural, forward-directed head lunge movement (Lardy et al., 2021).

If sufficient lunge space is not available, cows may direct their heads to the side when rising (Lidfors, 1989). Whether cows can fluidly lunge sideways into the neighbouring cubicle is largely determined by the design of the cubicle partitions (Bewley et al., 2017). Early cubicle partition designs focused primarily on stability and durability. These partitions typically contained bar work in the lateral lunge space and were combined with a rigid neck rail for structural support (Carlsson, 1999). Such partitions are still popular in the European Alpine region because of their long lifespan and low maintenance requirements, and because they can be conveniently wall-mounted in free-stalls with limited forward space, such as those converted from tie stalls. Later designs aimed to improve the lying comfort and movement space of cows, but often still contained bar work in the lateral lunge space (Veissier et al., 2004). Obstructions in the lateral lunge space impede lunging to the side, as cows must carefully aim their heads through the bar work if at all possible (Siebenhaar et al., 2012). In addition, the neck rail can hinder rising movements when placed too low (St John et al., 2021). Difficulties with rising can cause atypical behaviours, such as multiple head lunges, horse-like rising, and aborted rising attempts (Zambelis et al., 2019; Dirksen et al., 2020). Inadequate cubicle design is also associated with hesitation to lie down, which is reflected in a prolonged inspection phase and atypical behaviours such as repeated stepping (Lidfors, 1989; Haley et al., 2000; Dirksen et al., 2020). Cows unable to rise and lie down without excessive effort may mentally associate lying with pain, discomfort, and a lack of control (Lovarelli et al., 2020) and consequently lie down less frequently. In several studies, unfavourable lying conditions (reviewed in Tucker et al., 2021) and the incidence of abnormal rising behaviours (Zambelis et al., 2019) have been associated with a decreased lying frequency.

To address these issues, manufacturers of dairy housing installations have designed more permissive lying cubicles with open partitions and a flexible neck strap. The open frame partition with virtually no bar work in the lateral lunge space allows cows to use the space in neighbouring cubicles when lunging the head (Bewley et al., 2017). The flexible neck strap is presumably less painful than a rigid neck rail upon collision. Although sideways head lunging is still considered an atypical behaviour (Dirksen et al., 2020), facilitating sideways lunging might alleviate welfare issues in free-stalls where insufficient forward lunge space restricts natural rising. Experimental studies by Gwynn et al. (1991) and Ruud and Bøe (2011) suggest that cows prefer more permissive cubicle partitions (flexible and with fewer obstructions in the lateral lunge space). O'Connell et al. (1992) and Carlsson (1999) also found that cows prefer more open cubicle partitions when experimentally comparing differently shaped metal partitions. In another experimental study, Siebenhaar et al. (2012) reported that cows had more difficulty head lunging and showed increased hesitance before lying down with cubicle partitions with bar work in the lateral lunge space compared to more open partitions. To our knowledge, the effect of cubicle partition shape on dairy cow behaviour has not been investigated under real production conditions. Furthermore, the effect of flexible neck straps on dairy cow behaviour has not been previously researched.

In an observational study on commercial dairy farms, we investigated associations between lying cubicle design—more permissive versus more restrictive—and dairy cow lying behaviour under real production conditions in free-stalls with insufficient forward space. We compared the prevalence of atypical rising and lying down movements and the general lying behaviour (lying duration, lying frequency, and mean lying bout duration) of cows on farms with open partitions and a flexible neck strap (permissive cubicle type) with that of cows on farms with partitions that obstruct lateral head lunge movements and a rigid neck rail (restrictive cubicle type). We hypothesised that cows would have less difficulty rising and would show fewer signs of hesitance before lying down in the permissive cubicle type. Additionally, we expected cows to lie down more frequently in the permissive cubicle type because they would presumably be more comfortable rising and lying down.

2 Methods

2.1 Study design

Between November 2022 and March 2023, we examined the lying behaviour of free-stall housed dairy cows in two different types of lying cubicle designs on 10 commercial dairy farms in Switzerland. Farms with the permissive cubicle type (n = 4) had open partitions that facilitated lateral space sharing with the neighbouring cubicles and a flexible neck strap. Farms with the restrictive cubicle type (n = 6) had partitions that obstructed sideways movements through the partition frame and thus impeded lateral space sharing, and were fitted with a rigid neck rail (details in section 2.3).

We visited commercial dairy farms that already had one of the two partition designs installed. Thus, the farm was the experimental unit and the cow was the observational unit. The type of cubicle design could not be randomised across farms. Therefore, our study was observational and can show potential associations between cow lying behaviour and cubicle design, which may suggest but not prove causality. To limit confounding factors, we only included farms with lying cubicles that adhered to the following search criteria: exclusively wall-facing, bed length 185–200 cm, lunge space ≤70 cm, and deep bedded with a lime-straw mixture. The number of farms we included in our study was mainly limited by these search criteria, and by the willingness of farmers to participate.

2.2 Housing and animals

The farms participated voluntarily and were contacted with the help of dairy housing equipment dealerships (details on study farms in Supplementary Table S1 at https://doi.org/10.5281/zenodo.10639101). All farms had free-stalls with exclusively wall-facing deep-bedded lying cubicles (≥1 cubicle per cow) with a 20–30 cm high curb and brisket boards to retain the bedding material in the cubicles. All lying cubicles were sufficiently bedded with a lime-straw mixture so that both boards did not exceed the bedding surface by more than 10 cm, as required by Swiss legislation (FSVO, 2008b; Article 3). The lime-straw mixture provided a compact mattress so that the lying surfaces had sufficient compressibility to adequately conform to the shape of the cow when she was lying down. Farms maintained their cubicles 2 or 3 times per day (i.e., removing faeces and levelling of bedding material). Bed length and lunge space were similar across farms (max. 15 cm difference for both dimensions). The lunge space was between 60 and 70 cm on the farms with the permissive cubicle type, and between 55 and 70 cm on the farms with the restrictive cubicle type. These dimensions meet the minimum requirements of the Swiss legislation (FSVO, 2008b; Article 16), but are considered insufficient for adult cows for forward lunging (Dirksen et al., 2020). Within each farm, cubicle dimensions were consistent. The maximum difference in cubicle length between different rows on the same farm was <5 cm.

The herds consisted of 25 to 50 (mean ± SD = 33 ± 7.2) adult dairy cows of the breeds Brown Swiss and Holstein (Red Holstein and Holstein-Friesian). On each farm, we randomly selected 18–20 lactating cows. Cows that we saw limping or were reported by the farmer to have locomotion problems were not included. All farms practiced non-seasonal calving. In total, we collected data from 198 dairy cows (75 Brown Swiss and 123 Holstein). Their wither height ranged from 134 to 160 cm (mean ± SD = 149 ± 5.9 cm; Supplementary Table S1 at https://doi.org/10.5281/zenodo.10639101). During the data collection period, the cows had no pasture access, but they could access an outdoor exercise yard.

2.3 Lying cubicle design

The farms with the permissive cubicle type all had the CNS Surselva20 cubicle partition (Fig. 1; DeLaval AG, Switzerland). This partition was fixed to the floor at a single point, contained virtually no bar work in the lateral lunge space and had a chamfered back. The Surselva partition was always fitted with a flexible neck strap positioned at a mean height of 130 cm, which is higher than the Swiss recommendations (Zähner, 2009). The farms with the restrictive cubicle type had either the Thurgi partition (Fig. 1; DeLaval AG, Switzerland) or the Liegeboxenbügel Wandständig (Fig. 1; Krieger AG, Switzerland). The shape of these two partitions was similar, as they were both cantilevered to the wall and contained bar work in the lateral lunge space. Both restrictive partition models were always fitted with a steel neck rail positioned at a mean height of 110 cm, which is at the lower end of the Swiss recommendations (Zähner, 2009).

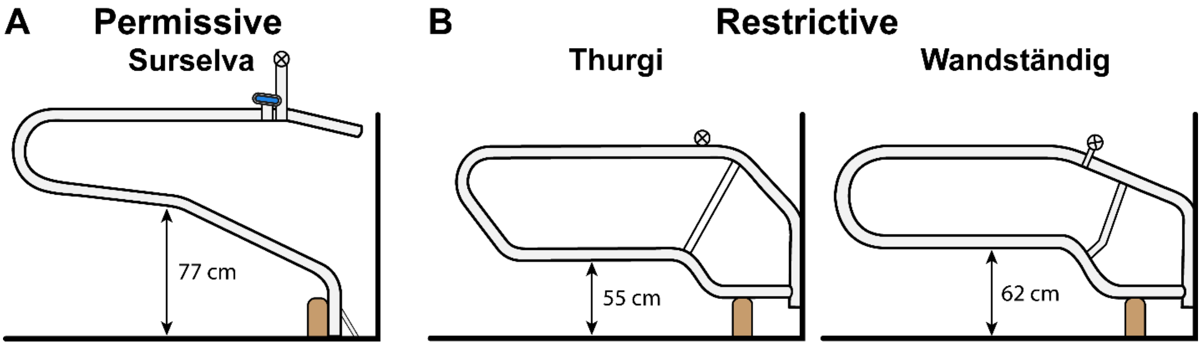

Figure 1. Cattle lying cubicle types examined in the study. (A) The permissive cubicle type featured open partitions with a chamfered back designed to facilitate lateral space sharing with the neighbouring cubicle (partition model Surselva). It also included a flexible neck strap and was fitted with a transverse waved bar positioned well above the wither height of the cows for structural support. (B) The restrictive cubicle type had partitions with bar work in the lateral lunge space (partition models Thurgi and Wändstandig) and a metal neck rail. Brown boxes indicate brisket boards.

2.4 Data collection

We recorded tri-axial acceleration at a sampling frequency of 5 Hz using accelerometers with a working range of ±15 g (MSR 145, MSR Electronics GmbH, Switzerland). These accelerometers were attached to the left hind leg of the cows on the outward-facing side of the metatarsus using a piece of foam and self-adhesive bandage. Attachment and removal were performed when the cows were fixed in a self-locking feed yoke during the morning feeding. The cows were given one day of habituation to get used to the accelerometers and to relieve the potential stress of attaching them (Fig. 2). The accelerometers recorded for 39 h, after which the internal memory was full. Concurrent to the acceleration data collection, continuous video recordings of the lying area were made. Depending on the layout of each barn, we installed one or two video cameras (Bascom 4XB40K, Bascom, Vianen, the Netherlands) at a height of 3 to 5 m. With a few exceptions, all lying cubicles were in view.

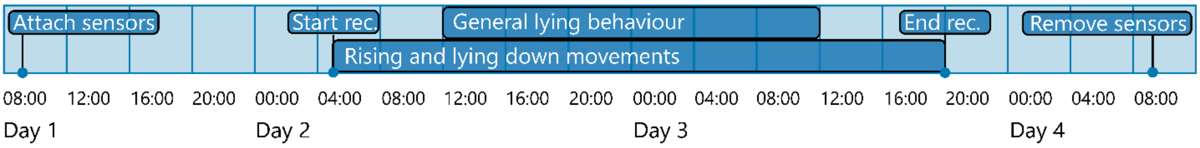

Figure 2. Timeline of data collection on farms and time windows used for data analyses. Accelerometers recorded for 39 h until the internal memory was full. Rising and lying down movements were analysed during the whole recording period until ≥5 rising events and ≥5 lying down events per cow were assessed. A time window of 24 h was used to analyse general lying behaviour. Abbreviations: rec. = recording.

2.5 Data processing and statistical analyses

2.5.1 Labelling of atypical rising and lying down behaviours

Data processing and statistical analyses were conducted in R (version 4.2.0; R Core Team, 2023). Rising and lying down movements were labelled for behaviours used in the evaluation of dairy cow housing conditions as proposed by Zambelis et al. (2019) and Dirksen et al. (2020; Table 1). These behaviours are atypical (i.e., not the norm) for dairy cows under spatially unrestricted conditions, but not all of them are necessarily harmful to the animal. For efficient labelling, the rising and lying down events in the videos were located based on the accelerometer data using the triact R package (version 0.3.0; Simmler and Brouwers, 2024). This drastically reduced the amount of video material to be analysed and allowed the individual cows to be identified reliably without physically marking them. If two cows rose or lied down from/on the same lying side at exactly the same time, the next posture transition event of one of the cows was examined to identify the individuals. The triact R package uses rule-based algorithms to distinguish between standing and lying postures and to determine the lying side based on which axis of the leg-mounted accelerometer gravity loads (see Simmler and Brouwers, 2024 for details). To locate the posture transitions, we followed the triact workflow using default settings, apart from specifying minimum_duration_lying = 0 when calling the *add_lying* method to ensure that we did not miss any posture transitions (rising or lying down). The few false positive posture transitions introduced as a result of deviating from using the default settings were manually discarded during the video analysis.

The identified posture transitions in the videos were labelled for atypical behaviours by one experienced observer (S.P.B.). It was not possible to blind the observer for cubicle type. Video material was analysed until ≥5 rising events and ≥5 lying down events per cow were assessed. Cows with either <5 rising events recorded clearly on video or <5 lying down events recorded clearly on video were not considered in the statistical analysis (10 of 198 cows, leaving 188 cows for statistical analysis). If the presence/absence of an individual atypical behaviour could not be determined (e.g., because another cow was standing partly in front of the focal cow), it was recorded as a missing value (Supplementary Table S2 at https://doi.org/10.5281/zenodo.10639101). To determine intra-observer reliability, the observer labelled 20 randomly selected rising events and 20 randomly selected lying down events a second time 2 months after completing the video analysis (Cohen's Kappa κ = 0.94).

We also used the triact R package to determine common measures for lying behaviour over 24 h (see the time window in Fig. 2). For each individual cow, we determined the daily lying duration, the lying frequency, and the mean lying bout duration. We followed the triact workflow using default settings for all parameters affecting the underlying algorithms.

Table 1. Ethogram of atypical behaviours in cattle during rising and lying down movements (source: Zambelis et al., 2019; Dirksen et al., 2020).

Atypical behaviour	Definition
Rising	
Horse-like rising (yes/no)	Cow first raises the forequarters and then the hindquarters.
Interruption (yes/no)	Hindquarters are lifted from the ground, but the rising movement is then terminated by lowering the hindquarters (to the same or other side of the body).
Staggered head lunge (yes/no)	Staggered, interrupted, or repeated motion of the head during the head lunge movement.
Sideways head lunge (yes/no)	Head lunge movement is directed sideways by bending the head and neck to the side.
Crawling backwards (yes/no)	When resting on carpal joints, cow moves her front leg(s) backwards after propelling herself.
Lying down	
Dog-sitting (yes/no)	Cow first lowers the hindquarters and then the forequarters.
Interruption[1] (yes/no)	Carpal joints touch the ground, but the lying down movement is then terminated by raising from the carpal joints.
Extensive inspection (yes/no)	Head is lowered and swept sideways (while sniffing the bed surface) more than 2 times before the lying down movement.
Repeated stepping (yes/no)	Stepping in place with front legs more than 2 times before the lying down movement.
Pawing (yes/no)	Pawing the bedding material with a front leg just before the lying down movement.

[1] We used the triact R package to support the video analysis; thus, we examined only actual lying down events with respect to interrupted events. Possible interrupted lying down events not shortly followed by a completed event were therefore not considered. However, based on Dirksen et al. (2020) and our own experience, we considered this to be very rare.

2.5.2 Statistical analyses

We investigated the associations between cubicle type on atypical rising and lying down behaviours and on measures of general lying behaviour using (generalised) linear mixed effects models from the R package lme4 (Bates et al., 2015). The model formulas in lme4 syntax were:

$$response \sim 0 + cubicleType + (1|farm/cow) + (1|breed)$$

As fixed effects, we included the categorical variable cubicle type (permissive or restrictive). The random effects included a random intercept for cow nested in farm to account for multiple observations per cow and for the potential effects of farm affiliation. Furthermore, a random intercept for breed was added to account for the potential effects of the breed. For models with measures of general lying behaviour as the response, the random effects were simplified to a random intercept for farm and breed, as here we had only a single observation per cow.

The generalised linear mixed effects models (GLMM) with atypical behaviours as the response were fitted with binominal response (yes/no) and logit link using the *glmer* function. The linear mixed effects models (LMM) with measures of general lying behaviour as the response were fitted with the *lmer* function. We checked underlying model assumptions using the R package DHARMa (Hartig, 2022; model diagnostics in Supplementary Figures S1–S3 at https://doi.org/10.5281/zenodo.10639101). We calculated contrasts between the permissive and restrictive cubicle type from the population-level fitted values (based only on the fixed effect estimates) obtained with the *predict.MerMod* function (parameters re.form = ∼0, type = “response”). We determined 95% quantile confidence intervals (95% CI) for fixed effects and contrasts through parametric bootstrapping as implemented in the *bootMer* function (104 bootstraps). This is considered to provide a more reliable indication of statistical significance than the p-values based on Wald statistics (Bates et al., 2015). A significant difference from the null hypothesis at the 0.05 level is indicated when the 95% CI does not include the null value (typically 0). However, we refrain from a discussion based on hard significance cut-offs and also consider the observed effect sizes with respect to biological relevance in our conclusions.

3 Results

Supplementary Figures and Tables and original data are available in the Zenodo repository (https://doi.org/10.5281/zenodo.10639101).

3.1 Atypical behaviours during posture transitions

We analysed the prevalence of atypical behaviours on 10 farms (experimental unit) in 188 cows (observational unit) by labelling a total of 1337 rising events and 1310 lying down events (Table 2). The observed durations of these events, including the inspection phase, are given in Supplementary Figure S4 at https://doi.org/10.5281/zenodo.10639101. In the restrictive cubicle type, 3 (0.4%) rising events were horse-like, and 4 (0.5%) rising events were interrupted (Supplementary Table S2 at https://doi.org/10.5281/zenodo.10639101). In the permissive cubicle type, horse-like rising was never observed, and 1 (0.2%) rising event was interrupted. Dog-sitting was not observed in either cubicle type. In the restrictive cubicle type, 4 (0.5%) lying down events were interrupted. In the permissive cubicle type, 1 (0.2%) lying down event was interrupted. We did not further analyse these rare atypical behaviours statistically.

Table 2. Number of farms, cows, rising events, and lying down events per cubicle type analysed for atypical behaviours.

	Cubicle type		
	Restrictive	Permissive	Total
Number of farms[1]	6	4	10
Number of cows[2]	113	75	108
Rising events	783	554	1337
Lying down events	801	509	1310

[1] Farm was the experimental unit

[2] Cow was the experimental unit

Fig. 3 shows the GLMM estimated probabilities of atypical behaviours during rising movements (staggered head lunge, sideways head lunge, and crawling backwards) in the restrictive and permissive cubicle type (random effect variance components in Supplemental Table S3 at https://doi.org/10.5281/zenodo.10639101). The GLMM estimated probabilities of staggered head lunging were 0.48 and 0.17 in the restrictive and permissive cubicle type, respectively. The GLMM estimated probabilities of sideways head lunging were 1.00 in both cubicle types. The GLMM estimated probabilities of crawling backwards were 0.02 and 0.01 in the restrictive and permissive cubicle type, respectively. Fig. 4 shows the estimated contrasts between the cubicle types for atypical rising behaviours. The estimated probability of staggered head lunging was 0.31 higher in the restrictive cubicle type (95% CI: 0.11–0.49). The estimated probability of crawling backwards was 0.01 higher in the restrictive cubicle type, however with weak statistical support (95% CI: 0.00–0.02). As we consider this effect size too small to be biologically relevant, we will not discuss it further. We did not find statistical support for an association between cubicle type and the probability of sideways head lunging.

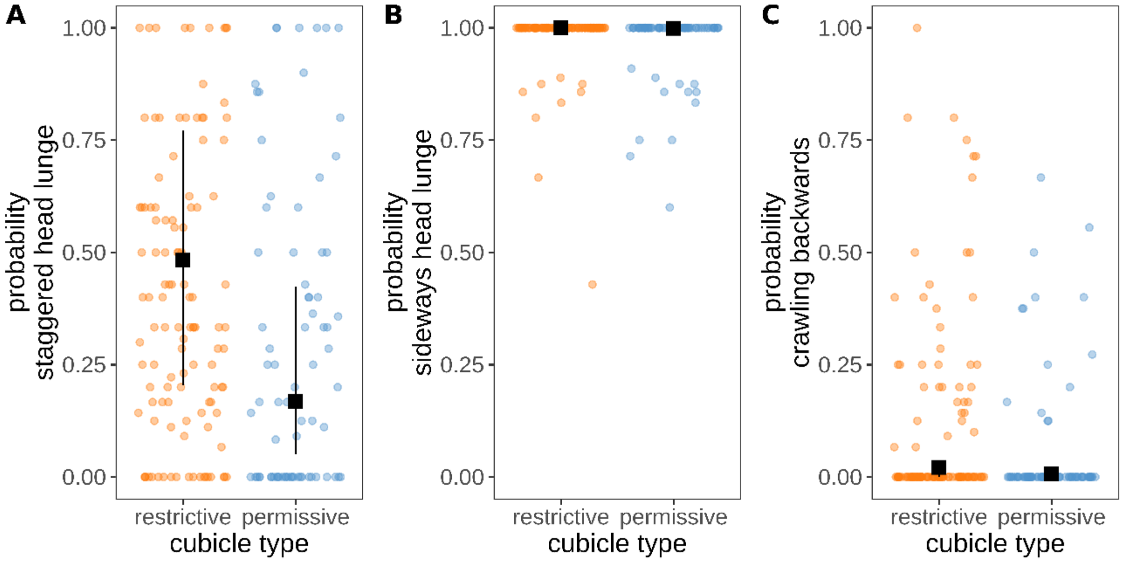

Figure 3. GLMM estimated probabilities (squares) with 95% CI (error bars) for atypical behaviours during rising (population level, considering only fixed effects): (A) staggered head lunge, (B) sideways head lunge, and (C) crawling backwards on the carpal joints. Coloured points represent observed proportions for individual cows (please note that model estimates are based on non-aggregated observations taking into account potential cow, farm, and breed effects). Abbreviations: GLMM = generalized linear mixed effects model; 95% CI = 95% quantile confidence interval.

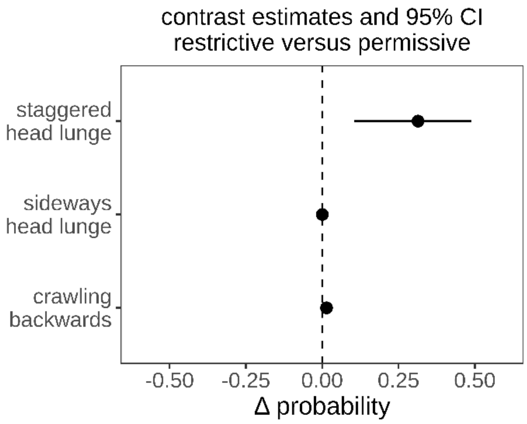

Figure 4. GLMM estimated contrasts (points) with 95% CI (error bars) between the restrictive cubicle type (reference) and permissive cubicle type for the probability that a cow performs atypical behaviours during rising: staggered head lunge, sideways head lunge, and crawling backwards. A statistically significant difference at the 0.05 level is indicated when the 95% CI does not include 0. Abbreviations: GLMM = generalized linear mixed effects model; 95% CI = 95% quantile confidence interval.

Fig. 5 shows the GLMM estimated probabilities of atypical behaviours prior to lying down movements (extensive inspection, repeated stepping, and pawing) in the restrictive and permissive cubicle type (random effect variance components in Supplemental Table S4 at https://doi.org/10.5281/zenodo.10639101). The GLMM estimated probabilities of extensive inspection were 0.35 and 0.21 in the restrictive and permissive cubicle type, respectively. The GLMM estimated probabilities of repeated stepping were 0.39 and 0.20 in the restrictive and permissive cubicle type, respectively. The GLMM estimated probabilities of pawing were 0.02 and 0.04 in the restrictive and permissive cubicle type, respectively. Fig. 6 shows the estimated contrasts between the cubicle types for atypical behaviours prior to lying down. The estimated probability of extensive inspection was 0.14 higher in the restrictive cubicle type, although with weak statistical support (95% CI: -0.03–0.32). The estimated probability of repeated stepping was 0.19 higher in the restrictive cubicle type, although with weak statistical support (95% CI: 0.00–0.38). We did not find statistical support for an association between cubicle type and the probability of pawing.

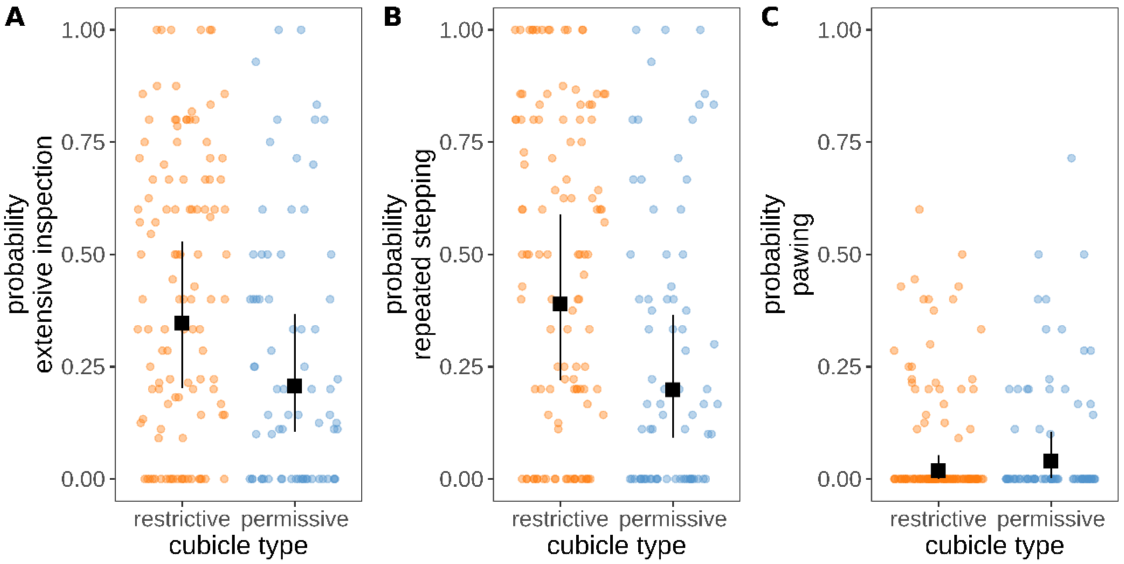

Figure 5. GLMM estimated probabilities (squares) with 95% CI (error bars) for atypical behaviours before lying down (population level, considering only fixed effects): (A) extensive inspection of the lying area, (B) repeated stepping with the front legs, and (C) pawing the bedding material. Coloured points represent observed proportions for individual cows (please note that model estimates are based on non-aggregated observations taking into account potential cow, farm, and breed effects). Abbreviations: GLMM = generalized linear mixed effects model; 95% CI = 95% quantile confidence interval.

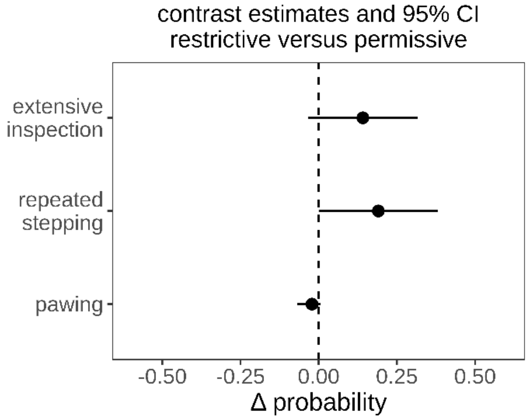

Figure 6. GLMM estimated contrasts (points) with 95% CI (error bars) between the restrictive cubicle type (reference) and permissive cubicle type for the probability that a cow performs atypical behaviours before lying down: extensive inspection, repeated stepping, and pawing. A statistically significant difference at the 0.05 level is indicated when the 95% CI does not include 0. Abbreviations: GLMM = generalized linear mixed effects model; 95% CI = 95% quantile confidence interval.

3.2 General lying behaviour

Fig. 7 shows the LMM estimates of daily lying duration, lying frequency, and mean lying bout duration with the restrictive and permissive cubicle type (random effect variance components in Supplemental Table S5 at https://doi.org/10.5281/zenodo.10639101). LMM estimates for daily lying duration were 10.6 and 12.5 h/day with the restrictive and permissive cubicle type, respectively. LMM estimates for lying frequency were 7.3 and 8.9 bouts/day with the restrictive and permissive cubicle type, respectively. LMM estimates for daily lying duration were 95 and 87 min per bout with the restrictive and permissive cubicle type, respectively. Fig. 8 shows the estimated contrasts between the cubicle types for measures of general lying behaviour. The estimated daily lying duration was 1.9 h/day lower with the restrictive cubicle type (95% CI: 0.5–3.4 h/day). The estimated lying frequency was 1.6 bouts per day lower with the restrictive cubicle type, although with weak statistical support (95% CI: 0.2–3.1 bouts/day). We did not find statistical support for an association between cubicle type and the mean lying bout duration.

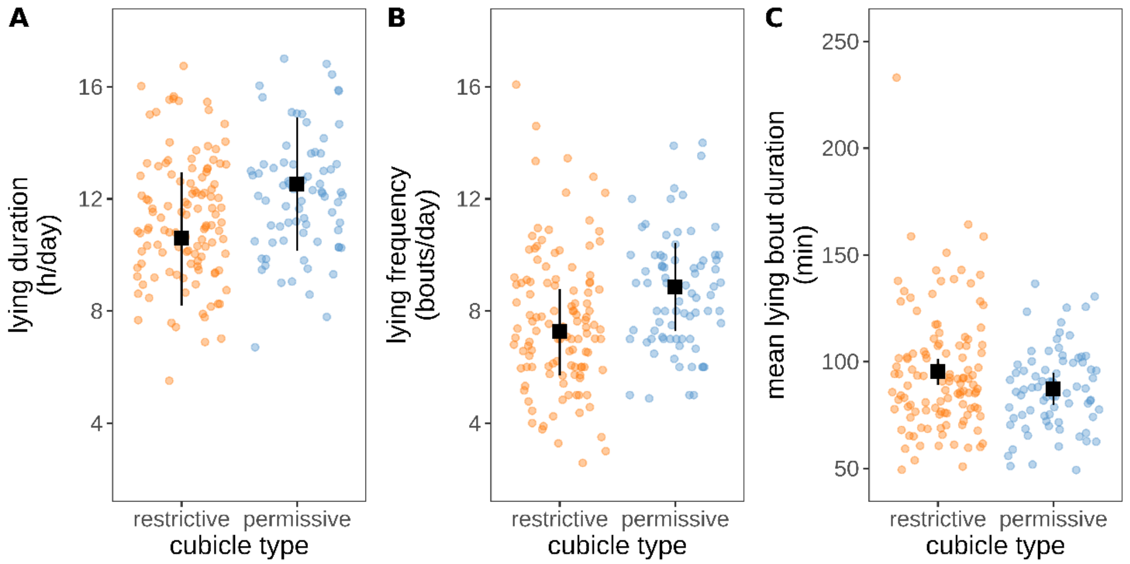

Figure 7. LMM estimated probabilities (squares) with 95% CI (error bars) for measures of general lying behaviour (population level, considering only fixed effects): (A) daily lying duration, (B) number of lying bouts per day, and (C) mean lying bout duration. Points represent observations for individual cows (please note that model estimates take into account potential farm, and breed effects). Abbreviations: LMM = linear mixed effect model; 95% CI = 95% quantile confidence interval.

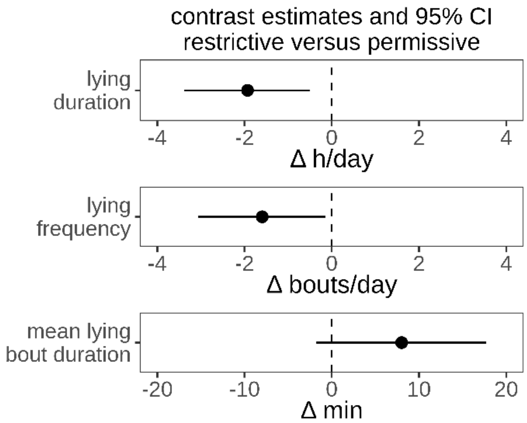

Figure 8. LMM estimated contrasts (points) with 95% CI (error bars) between the restrictive cubicle type (reference) and permissive cubicle type for daily lying duration, lying frequency, and mean lying bout duration of cows. A statistically significant difference at the 0.05 level is indicated when the 95% CI does not include 0. Abbreviations: LMM = linear mixed effect model; 95% CI = 95% quantile confidence interval.

4 Discussion

In general, all lying cubicles in this study met the minimum Swiss animal welfare requirements, which should allow cows to rise and lie down according to their species-specific movement patterns (i.e., no horse-like rising and dog-sitting; FSVO, 2008a; Article 8). In addition, cows almost never interrupted rising or lying down movements with either cubicle type. These results are in line with Dirksen et al. (2020) and Brouwers et al. (2023), who found that horse-like rising, dog-sitting, and interrupted posture transitions were rare in lying cubicles with dimensions similar to our study.

The cows in our study performed nearly exclusively sideways head lunges when rising in both cubicle types. Thus, our results provide evidence that lunge spaces of ≤70 cm are not sufficient for cows of 140–160 cm wither height to perform the natural forward head lunge when rising. In contrast, Dirksen et al. (2020) estimated the probability of sideways head lunging to be around 0.50 for cubicles with small lunge spaces, without separating wall-facing and head-to-head cubicles in the analysis. However, from Fig. 1F in Dirksen et al. (2020), it appears that cows in wall-facing cubicles predominantly performed sideways head lunges, as in our study. It is interesting to note that cows in the restrictive cubicle type with partitions with bar work in the lateral lunge space were able to lunge their heads sideways. They were generally not observed to lunge upwards or to resort to horse-like rising, as has been reported for cubicles with a very small lunge space and partitions that severely restrict lateral space sharing (reviewed in Lidfors, 1989).

The probability of staggered head lunging was around 0.30 lower in the permissive cubicle type. This observed difference may be related to the reduced need for cows to aim their head between bar work with the open partitions. Other plausible explanations could be the difference between the flexible neck strap and the rigid neck rail, as cows anticipating a collision with a rigid neck rail may be more hesitant when lunging their heads. However, the probability of crawling backwards was close to zero in both cubicle types. This may suggest that the neck rails in this study were generally installed at sufficient heights for cows to rise without collisions. However, due to the small lunge spaces, it is likely that the cows were lying close to the rear curb without their backs under the neck rail, thereby mitigating the influence of the neck rail on rising behaviour. Our findings are in line with Siebenhaar et al. (2012), who also reported a decrease in staggered head lunge movements when comparing cubicle partitions with bar work in the lateral lunge space to more open partitions. Thus, open partitions appear to be associated with more fluid sideways head lunges, which may explain the observed preferences of dairy cows for more cubicle partitions with less bar work in the lateral lunge space by O'Connell et al. (1992) and Carlsson (1999). Altogether, this might suggest that facilitating lateral space sharing can alleviate difficulties with head lunging in cubicles that do not allow for forward lunging. However, it is important to note that sideways head lunging is a behavioural adaptation to insufficient forward space and is not common on pasture (Brouwers et al., 2022). Furthermore, sideways head lunging may be uncomfortable for cows due to the strain on the neck muscles (Dirksen et al., 2020), and even in the permissive cubicle type, staggered head lunging was around twice as common as observed on pasture (Brouwers et al., 2022).

In addition to the lower prevalence of staggered head lunges, cows in the permissive cubicle type also performed fewer behaviours indicative of hesitance prior to lying down (extensive inspection and repeated stepping). This is in line with Wilson et al. (2022) who observed a shorter duration of the inspection phase before lying down in experimental lying cubicles with minimal partitions and no neck rail. Inspection of the lying area is a natural behaviour and performed on pasture (Lidfors, 1989). However, extensive inspection (i.e., repeated head pendulum movements) has been associated with suboptimal housing conditions, such as insufficient bedding material (Müller et al., 1989) and tethering (Haley et al., 2000). Our findings are partially in line with Siebenhaar et al. (2012), who observed a higher frequency of repeated stepping with the front legs with obstructed partitions compared to open partitions, but found no difference in the prevalence of extensive inspection of the lying area. The greater hesitancy to lie down that we observed in restrictive cubicles may have been induced by previous negative (painful) experiences during rising or lying down, such as the inability to perform a fluid head lunge or collisions with the flank against the partition when lying down. However, the hesitance to lie down may also be related to the differences between flexible neck straps and rigid neck rails. For example, it may have been more uncomfortable for the cows to stand fully inside restrictive cubicles because the lower-positioned and rigid neck rail pressed more against their necks in this position.

Although not systematically recorded, we observed multiple instances of cows becoming trapped in or under partitions of the restrictive cubicle type when attempting to rise. This usually occurred because the cows required multiple head lunges and shifted forward with each lunging attempt, getting their heads stuck in the bar work of the partition. Such events have serious welfare consequences as animals lose control over their environment and can suffer traumatic injuries.

Daily lying duration, lying frequency and mean lying bout duration were generally within typical ranges for dairy cows (reviewed in Tucker et al., 2021). However, lying frequency was higher with the permissive cubicle type compared to the restrictive cubicle type. The higher probability of staggered head lunging in the restrictive cubicle type was thus associated with a lower lying frequency, a relationship also previously reported by Zambelis et al. (2019). A decreased lying frequency is generally linked to unfavourable lying conditions (Rushen et al., 2007; Bouffard et al., 2017). Thus, our results might suggest that the difference in lying frequency between permissive and restrictive cubicle types is related to the willingness of cows to transition between standing and lying in cubicles with a small lunge space.

In addition to the increased lying frequency, daily lying duration was also higher with the permissive cubicle type. The difference of nearly 2 hours per day is biologically relevant as cows lie between 8 and 13 hours per day on average (Tucker et al., 2021). The relationship between changes in lying duration and lying comfort is not entirely clear (Tucker et al., 2021). Nevertheless, our observations might suggest that cows were more comfortable when lying in permissive cubicles. This may be due to the absence of bar work in the lateral lunge space and/or because of the chamfered back of the open partition (Fig. 1). The chamfered back allows for more space sharing with the hips and gives cows more freedom to adopt different lying positions. However, our estimates of general lying behaviour are based on only 1 day of accelerometer data per cow. Ito et al. (2009) found that 3 days of recording provided excellent estimates of farm-level means calculated from 5 days of recording (R2 = 0.94 and 0.95 for daily lying duration and lying frequency, respectively), while using only 1 day provided less reliable estimates ($R2$ = 0.74 and 0.77 for daily lying duration and lying frequency, respectively). This may suggest that using 3 days of recordings instead of 1 day would have reduced the uncertainty in the estimates in our study. We used 1 day of recordings because of the limited storage capacity of our accelerometers and because we wanted to record at 5 Hz to further develop the detection models proposed in Brouwers et al. (2023).

We studied the lying behaviour of cows in two different types of cubicle design under real production conditions on commercial farms. The type of cubicle design could therefore not be randomised (see section on study design). Thus, the study is observational and comes with the challenge of being susceptible to confounding factors. Through the selection of the study farms, we aimed to limit confounding by factors known to influence rising behaviour (lunge space size, wall-facing versus head-to-head cubicle orientation; Dirksen et al., 2020). However, it is likely that our response variables, particularly measures of general lying behaviour, are influenced by factors not accounted for in our study. Due to the observational nature of this study, any observed associations between cubicle type and our response variables can only suggest, not confirm, causation. Consequently, randomised experiments are necessary to verify the hypotheses derived from our observations.

Conclusion

A permissive lying cubicle design with open partitions and a flexible neck strap positioned relatively high above the lying surface was associated with reduced prevalence of staggered head lunge movements during rising, less signs of hesitance before lying down, and increased lying frequency and daily lying duration. The estimates of general lying behaviour (lying frequency and duration) should be interpreted with caution due to the short data collection period (1.5 days). Despite this limitation, our findings might suggest that this permissive cubicle design can improve conditions for dairy cows to rise and lie down in free-stalls with a small lunge space (≤70 cm in this study). However, wherever possible, the first priority should be to increase the lunge space to allow for natural rising behaviour (forward lunging), and cubicles that require sideways head lunging are a compromise at best. If it is not possible to increase forward lunge space, permissive cubicle design with open cubicle partitions and a flexible neck strap may help improve dairy cow welfare in free-stalls with insufficient lunge space.

Ethics approval

Ethical approval for the study was obtained from the Veterinary Office of the Canton Thurgau, Switzerland (TG03/2021, Approval No. 33448).

Data and model availability statement

The data that supports the study findings are publicly available in the Zenodo repository (https://doi.org/10.5281/zenodo.10639101).

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Appendix III

Brouwers, S. P., Schug, A. F. E., Simmler, M., and Savary P.

2024

The effect of neck strap positioning relative to dairy cow body size on rising and lying down behaviours and lying cubicle hygiene

Animal, submitted September 2024

Abstract

In cubicle housing systems for dairy cows, neck rails/straps/chains are used to limit bedding soiling by faeces and urine. Flexible neck straps are an alternative to rigid neck rails, which are associated with animal welfare issues such as painful collisions, injuries, and atypical behaviours. However, no literature exists on the positioning of flexible neck straps in relation to their effectiveness in limiting soiling of the bedding material and their effect on cow behaviour. In a research barn with two pens of 20 cows each, we investigated how neck strap positioning relative to cow body size affects rising and lying down behaviours, general lying behaviour, and defecation behaviour in lying cubicles. To expand the range of relative positioning beyond that resulting from the herd's variation in body size, we varied the neck strap height (105, 120, and 135 cm) and its distance from the curb (155 and 170 cm) in two experiments. The resulting ratios of neck strap height to withers height (NSH ratio) ranged from 0.65 to 0.96, and the ratios of neck strap distance from the curb to diagonal body length (NSD ratio) ranged from 0.85 to 1.11. With the exception of sideways head lunging, atypical rising and lying down behaviours were rare throughout the study. A higher NSH ratio was associated with a reduced probability of crawling backwards on the carpal joints during rising. We found no statistical support for an effect of neck strap positioning relative to cow body size on the probabilities of other atypical rising and lying down behaviours, or daily lying time and frequency. For defecations within a 120 s time window around rising events while in the lying cubicle, a higher NSH ratio was associated with a higher probability of faeces landing in the cubicle. This probability also increased with increasing NSD ratio. Overall, our results indicate that the positioning of flexible neck straps relative to cow body size, as tested in this study, does not considerably affect dairy cow behaviour, suggesting that flexible straps can accommodate cows of different sizes. The effectiveness of positioning cows in the lying cubicle in such a way that limits soiling of the bedding around rising events increased with a lower NSH ratio. Thus, flexible neck straps can be a viable alternative to rigid neck rails by limiting soiling of lying cubicles around rising events without considerably impeding dairy cow movements during rising and lying down.

1 Introduction

Cubicle housing systems should allow dairy cows to lie down and rest comfortably on a clean and dry lying surface. Therefore, the design and configuration of lying cubicles should limit soiling of the bedding material while minimising the hindrance of other behaviours. Typically, a rigid neck rail or flexible neck strap or chain is placed across the cubicle partitions to encourage cows to stand in the lying cubicle with their hind legs close to the rear curb so that faeces and urine fall into the walking alley and do not soil the bedding material (van Eerdenburg & Ruud, 2021). Together with the brisket board, the neck rail/strap should also guide cows to lie down near the end of the lying cubicle to limit bedding soiling by lying cows and to ensure that cows have sufficient space to lunge their heads when rising. The effectiveness of the neck rail/strap/chain depends on both the height above the lying surface and the distance from the curb at which it is installed (Cook & Nordlund, 2005). To prevent cows from standing and lying too far forward in the lying cubicle, the neck rail/strap/chain should be placed below the cows' wither height (Veissier et al., 2004). However, the space required for a cow to rise and lie down is proportional to her body size. Therefore, neck rails/straps/chains should be positioned relative to cow body size (CIGR, 2014; EFSA, 2023).

For rigid neck rails, the influence of their positioning on lying cubicle hygiene and dairy cow welfare has been extensively studied. Restrictive neck rail positioning can cause cows to collide with the rail when rising, resulting in abrasions, bruises, and even fractures (Cermak, 1988; Veissier et al., 2004). It can also increase the prevalence of lameness and hoof disease by forcing cows to stand in the walking alley, which contains manure (Bernardi et al., 2009; Gieseke et al., 2020). Conversely, overly permissive neck rail positioning or the complete absence of neck rails is associated with a reduction in both lying cubicle and animal cleanliness (Robles et al., 2021; Tucker et al., 2005; Wilson et al., 2022). Therefore, overly permissive neck rail positioning increases the need for cubicle maintenance and may increase the risk of udder infections (Breen et al., 2009). However, positioning the neck rail so that all cows can stand with four hooves in the cubicle and are not hindered in their natural movements, while limiting soiling of the bedding, is virtually impossible due to the natural variation in cow body size in commercial herds (de Boyer des Roches et al., 2019; Rushen, 2017).

Flexible neck straps are considered as an alternative to neck rails because they may reduce the animal welfare problems associated with rigid neck rails. Collisions with a flexible strap are presumably less painful and chances of injury lower compared to rigid neck rails. However, there is no scientific literature on the positioning of flexible neck straps in relation to their effectiveness in limiting soiling of the bedding material and their effect on cow behaviour. Therefore, the aims of the current study were to investigate the effects of neck strap positioning relative to cow body size on rising and lying down behaviours, general lying behaviour, and defecation behaviour in lying cubicles.

2 Methods

2.1 Housing

The study took place in October and November 2023 in a research barn of Agroscope (Aadorf TG, Switzerland). The barn consisted of two identical (mirrored), spatially separated pens. Each pen contained two rows of seven head-to-head lying cubicles and one row of six wall-facing lying cubicles. All lying cubicles were deep-bedded with a lime-straw mixture with a bedding depth of approximately 15 cm. Faeces were removed and the bedding was levelled (adding bedding if necessary) three times a day: before morning milking, after fresh feed was provided, and before afternoon milking. The individual lying cubicles measured 125 cm in width and were separated by partitions of the Liberty model (Fig. 1; Krieger AG, Switzerland). The cubicles had a brisket board located 195 cm from the inside of the rear curb with a height of 5–10 cm above the bedding, depending on the bedding level. Wall-facing lying cubicles had a lunge space of 80 cm. In head-to-head cubicles, the space between opposite brisket boards was 105 cm and opposing rows were separated by a front rail positioned in the centre of the lunge space at a height of 100 cm above the brisket board. All lying cubicles were fitted with a flexible neck strap (Fig. 1A; Krieger AG, Switzerland) made of nylon lashing strap material, angled at approximately 45° and tightened with a cogwheel tensioner fixed to the end gate of each lying cubicle row. In the period prior to the experiments, the neck straps were positioned at a height of 105 cm above the bedding and 155 cm from the rear curb in all lying cubicles, and the front rails were positioned at a height of 80 cm above the brisket board in the head-to-head cubicles. At the start of the study, all neck straps were replaced with new ones.

The alleys were covered with rubber mats and cleaned 12 times a day by automatic scrapers. Cows were fed ad libitum a total mixed ration consisting of grass silage, maize silage, and minerals. Fresh feed was provided daily at 0800 h, and the feed was pushed up 18 times per day. Additionally, concentrate was offered at an automated feeding station according to the animal-individual allowance. The cows were locked in the headlock feeder for approximately 1 h after fresh feed was provided. The cows did not have access to pasture or the outdoor exercise yard during the study. Water was freely available from two self-filling troughs per pen. The cows were milked twice daily at 0500 h and 1600 h. The research barn was managed alternately by two staff members.

2.2 Animals

In both pens, the dairy herd consisted of 20 primiparous and multiparous lactating cows of the Brown Swiss and Swiss Fleckvieh breeds. The herds were balanced as best as possible with respect to breed, age, parity, days in milk, wither height, and diagonal body length (Table 1). Prior to the experiment, the cows were housed either in the barn where the experiment took place or in a nearby barn (Ettenhausen TG, Switzerland) with similar lying cubicle dimensions, partitions, and neck straps. The herds were established 1 week before the start of the experiment.

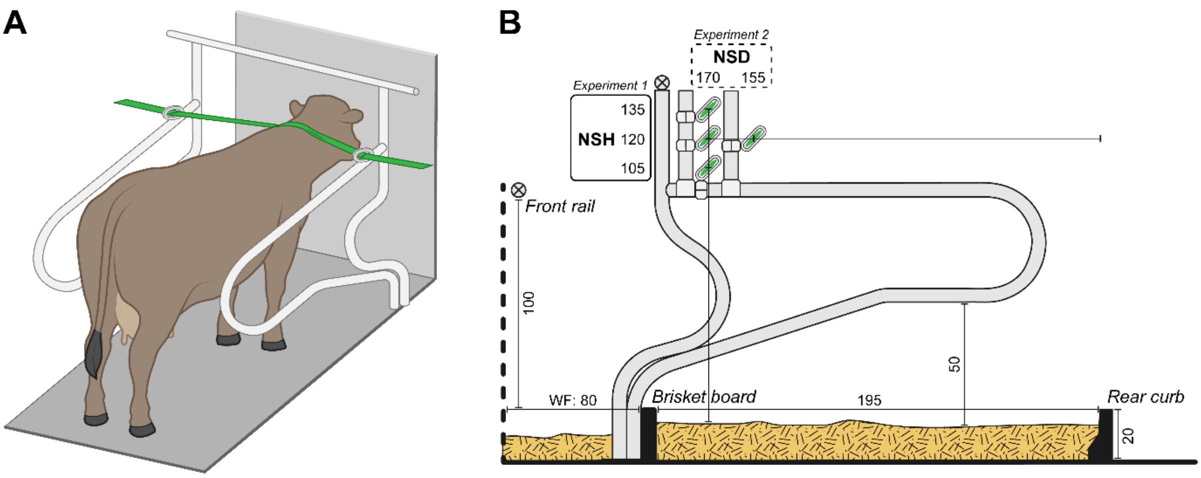

Figure 1. (A) Illustration of a dairy cow standing in a lying cubicle fitted with a flexible neck strap across the partitions. The flexibility of the neck strap allows the cow to stand with all four hooves in the cubicle, but discourages her from walking forward by pushing against her neck. (B) Lying cubicle dimensions (cm), and neck strap positions (cm) investigated in Experiment 1 (solid square) and Experiment 2 (dashed square). Abbreviations: NSH = neck strap height; NSD = neck strap distance from the curb; WF = wall-facing cubicles.

Table 1. Characteristics of the dairy cows in the study population (all values represent mean ± SD).

	Pen A	Pen B
Breeds	12 Brown Swiss, 8 Swiss Fleckvieh	12 Brown Swiss, 8 Swiss Fleckvieh
Age (years)[1]	4.3 ± 1.43	4.7 ± 1.80
Parity[1]	2.3 ± 1.22	2.8 ± 1.62
Days in milk[1]	51 ± 38.4	54 ± 42.0
Wither height (cm)	149 ± 5.8	151 ± 4.9
Diagonal body length (cm)	171 ± 7.3	168 ± 5.8

[1]At the start of Experiment 1.

2.3 Study design

We investigated the effects of neck strap positioning relative to cow body size on dairy cow behaviour by conducting two experiments in direct succession. A digital hanging suspension scale was used to control the tension of the neck strap. The neck straps were tightened to the point where it took a pulling force of 147 N (15 kg on the scale) to stretch the neck strap 10–12 cm upwards. This was measured again on day 3 of each experiment week and the neck straps were tightened if they stretched more than 12 cm.

2.3.1 Experiment 1: Neck strap height relative to cow wither height

We investigated the effects of neck strap height (NSH) relative to cow wither height (NSH ratio; Eq. 1) on dairy cow behaviour in lying cubicles, namely atypical rising and lying down behaviours, general lying behaviour, and defecation behaviour around rising events. NSH was defined as the vertical distance from the bedding surface to the midpoint of the neck strap, considering the strap's 45° angle. To increase the range of variation in NSH ratio beyond that resulting from the herd's variation in wither height (Table 1), we adjusted the NSH in the two pens to 105, 120, and 135 cm (Fig. 1B) for one week each, in the order shown in Table 2. The resulting NSH ratios ranged from 0.65 to 0.96. To change the NSH, we installed a short metal pipe on each lying cubicle partition (Fig. 1B). We slightly compressed the bedding to form a flat surface when measuring NSH. In Experiment 1, the neck strap was always positioned at 170 cm from the curb (measured from directly above the inner edge of the rear curb).

$$NSH\ ratio = \frac{NSH\ (cm)}{wither\ height\ (cm)} \qquad (1)$$

Table 2. Experimental design of Experiment 1 and Experiment 2.

	Experiment 1			Experiment 2	
	Week 1	Week 2	Week 3	Week 4	Week 5
Pen A	105 cm	135 cm	120 cm	155 cm	170 cm
Pen B	120 cm	105 cm	135 cm	170 cm	155 cm

Abbreviations: NSH = neck strap height; NSD = neck strap distance from the curb.

2.3.2 Experiment 2: Neck strap distance from the curb relative to cow diagonal body length

We investigated the effects of neck strap distance from the curb (NSD) relative to cow diagonal body length (NSD ratio, Eq. 2) on dairy cow behaviour in lying cubicles, namely atypical rising and lying down behaviours, general lying behaviour, and defecation behaviour around rising events. NSD was defined as the horizontal distance from directly above the inner edge of the rear curb to the midpoint of the neck strap, considering the strap's 45° angle. To increase the range of variation in NSD ratio beyond that resulting from the herd's variation in diagonal body length (Table 1), we adjusted the NSD in the two pens to 155 and 170 cm (Fig. 1B) for one week each, in the order shown in Table 2. The resulting NSD ratios ranged from 0.85 to 1.11. To change the NSD, the short metal pipe was moved backwards or forwards relative to the curb. In Experiment 2, the NSH was fixed at 120 cm.

$$NSD\ ratio = \frac{NSD\ (cm)}{diagonal\ body\ length\ (cm)} \qquad (2)$$

2.4 Data collection

On day 2 of each experiment week, triaxial accelerometers (MSR 145; MSR Electronics, Switzerland) recording at 1 Hz were attached to the outward-facing side of the left metatarsus of each animal using a piece of foam and self-adhesive bandage when the cows were fixed in the headlock feeder during feeding. Accelerometer recording started at 1200 h on experiment day 3 and ended at 0800 h on day 1 of the following experiment week, after which the accelerometers were removed, read out, and recharged. Two cameras (Bascom 4XB40K, Bascom, Vianen, The Netherlands) were installed in each pen at a height of approximately 4 m so that all lying cubicles and walking alleys were in view. Continuous video recordings were made. The cameras had built-in infrared lights for night-time recording.

2.5 Data processing and analysis

2.5.1 General lying behavior

Data processing and statistical analyses were conducted in R (version 4.2.3; R Core Team, 2023). General lying behaviour was analysed using the accelerometer data from days 4 to 7 of each experiment week using the triact R package (version 0.3.0; Simmler & Brouwers, 2024) with default parameter settings. This R package uses a simple rule-based algorithm to distinguish between standing and lying postures, based on the axis of the leg-mounted accelerometer on which the reaction force of gravity loads. For each cow, daily lying time, lying frequency, and mean lying bout duration were determined from days 4 to 7 of each experiment week. Due to the change from Central European Summer Time to Central European Time, the milking and feeding times on days 6 and 7 of experiment week 2 were shifted by +1 h with respect to our observation period. In order to account for this and other potential differences between weeks, the statistical analysis includes week as a factor (see *Statistical analysis*).

2.5.2 Atypical rising and lying down events

For days 4 to 7 of each experiment week, rising and lying down events were located in the video footage using the timestamps obtained with the *extract_liedown* and *extract_standup* functions of the triact R package. From these events, we randomly selected three clearly observable rising and three lying down events between 0500 h and 2000 h per cow per day for assessment of atypical behaviours using an ethogram based on Brouwers et al. (2023; Table 2). Events were considered clearly observable if lighting conditions were good and the focal cow was not obstructed by other cows. In a few cases (3% of cow-days), only two or one clearly visible event(s) were available. Additionally, we assessed defecation behaviour in lying cubicles within a 120 s time window around the selected rising events (centred around the end of the rising events; Table 3), thus analysing defecations shortly before and shortly after rising events. When a cow exited the cubicle within 60 s after rising and defecated in the walking alley, this was not recorded. Cows were sometimes tethered to the lying cubicle for a few hours if they needed veterinary treatment or if they were close to oestrus (i.e., if they were mounting other cows). Rising and lying down events of tethered cows were not considered; instead, the next closest event of that cow, if available, was selected for analysis. Throughout the study, rising and lying down events were analysed by two trained observers (SPB and AFES). Both observers analysed two days per experiment week per pen. The observers could not be blinded to the position of the neck strap. To determine interobserver reliability, the observers assessed the same set of 50 randomly selected rising events and 50 randomly selected lying down events (Cohen's Kappa $\kappa = 0.88$).

Table 2. Ethogram of atypical behaviours in cattle during rising and lying down (source: Brouwers et al., 2023).

Behaviour	Definition
Rising	
Horse-like rising (yes/no)	Cow first raises the forequarters and then the hindquarters.
Interruption (yes/no)	Hindquarters are lifted from the ground, but the rising movement is then terminated by lowering the hindquarters (to the same or other side of the body).
Staggered head lunge (yes/no)	Staggered, interrupted, or repeated motion of the head during the head lunge movement.
Sideways head lunge (yes/no)	Head lunge movement is directed sideways by bending the head and neck to the side.
Crawling backwards (yes/no)	When resting on carpal joints, cow moves her front leg(s) backwards after propelling herself.
Lying down	
Dog-sitting (yes/no)	Cow first lowers the hindquarters and then the forequarters.
Interruption[1] (yes/no)	Carpal joints touch the ground, but the lying down movement is then terminated by raising from the carpal joints.
Extensive inspection (yes/no)	Head is lowered and swept sideways (while sniffing the bed surface) more than 2 times before the lying down movement.
Repeated stepping (yes/no)	Stepping in place with front legs more than 2 times before the lying down movement.
Pawing (yes/no)	Pawing the bedding material with a front leg just before the lying down movement.

[1] We used the triact R package to support the video analysis; thus, we only assessed actual lying down events with respect to interrupted events. Possible interrupted lying down events not shortly followed by a completed event were therefore not considered. However, based on Dirksen et al. (2020) and Brouwers et al. (2024), we considered this to be very rare in lying cubicles complying with Swiss legislation.

Table 3. Ethogram of defecation behavior around rising events.

Behaviour	Definition
Defecation	Cow defecates within a 120 s time window centred around the end of the rising event while in the lying cubicle [1]
Posture (standing with four hooves in the cubicle/standing with only the front hooves in the cubicle/lying in the cubicle)	Posture of the cow at the start of the defecation
Location (cubicle/walking alley)	Location where the majority of the faeces lands

[1] End of rising event: cow is standing with all four hooves in contact with the floor, in a balanced position.

2.6 Statistical analysis

We used (generalised) linear mixed effects models (GLMMs/LMMs) from the R packages lme4 (Bates et al., 2015). Fixed effects and odds ratios were obtained from population-level estimates obtained using the *predict.MerMod* function with the parameter re.form = ~0. Corresponding 95% bootstrap quantile confidence intervals/bands (95% CI) were obtained by parametric bootstrapping using the *bootMer* function (10^4 bootstraps). This is considered to provide a more reliable indication of statistical significance than p-values based on Wald statistics (Bates et al., 2015). A significant difference from the null hypothesis at the 0.05 level is indicated when the 95% CI does not include the null value (0 for fixed effects, 1 for odds ratios). For all models, we checked the underlying model assumptions using the DHARMa R package (Hartig, 2022).

2.6.1 Atypical rising and lying down behaviours and general lying behaviour

We investigated the effects of NSH ratio and NSD ratio on atypical rising and lying down behaviours and general lying behaviour using (G)LMMs with formulae in lme4 syntax as follows:

$$response \sim 1 + ratio + (1|pen/cow) + (1|week)$$

Fixed effects included a general intercept and a slope for NSH ratio or NSD ratio, respectively (1 + ratio). Random effects included a random intercept for cow nested within pen (1|pen/cow) to account for multiple observations of the same cow and the potential effects of pen affiliation. Furthermore, a random intercept for week was included (1|week). The GLMMs with atypical behaviours as the response were fitted with a binominal response (yes/no) and a logit link using the glmer function. We used the GLMM estimates to calculate odds ratios for a 0.1 increase in NSH ratio or NSD ratio. A 0.1 increase in NSH ratio corresponds to a 15 cm higher neck strap for a cow with a wither height of 150 cm. The LMMs with measures of general lying behaviours as response were fitted with the *lmer* function.

2.6.2 Defecation behaviour around rising events

We investigated the effect of NSH ratio and NSD ratio on the probability that faeces lands in the lying cubicle around rising events using GLMMs with the same structure as the models described in the preceding section. Furthermore, we analysed the data on defecation behaviour around rising events in more detail using Item Response Tree (IRTree) GLMMs (López-Sepulcre et al., 2015). The data were encoded as a binary response tree with six nodes (Fig. 2). Node 1 indicated whether the cow defecated within the 120 s time window while in the lying cubicle (1: yes; 0: no). If yes, Node 2 indicated whether the cow defecated while standing (1: yes; 0: no). If the cow defecated while standing, Node 3 indicated whether the cow was standing with all four hooves in the lying cubicle at the start of the defecation (1: yes; 0: no). If the cow was lying at the start of the defecation, Node 4 indicated whether faeces landed in the lying cubicle (1: yes; 0: no). If the cow was standing with all four hooves in the lying cubicle at the start of the defecation, Node 5 indicated whether faeces landed in the cubicle (1: yes; 0: no). Lastly, if the cow was standing with only the front hooves in the lying cubicle at the start of the defecation, Node 6 indicated whether faeces landed in the cubicle (1: yes; 0: no). Node 6 was ultimately not included in the IRTree model because all responses at this node were 0 (no). The IRTree model was estimated as a GLMM with a binominal response (yes/no) and a logit link function using the *glmer* function. The model formulae in lme4 syntax were as follows:

$$response \sim 0 + node + node{:}ratio + (0 + node|pen/cow) + (0 + node|week) + (1|obs)$$

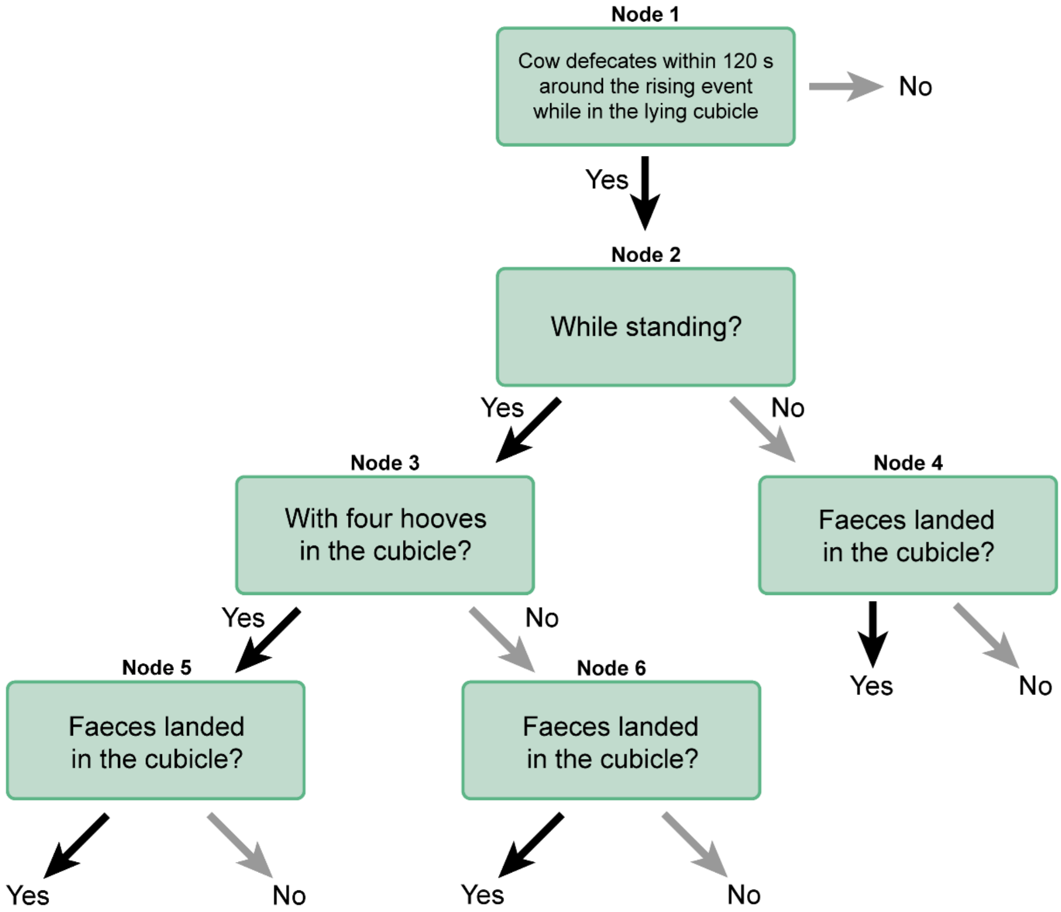

Figure 2. Binary response tree for elimination behaviour of dairy cows around rising events. Black arrows represent outcomes coded as 1 in the binomial trial; grey arrows represent outcomes coded as a 0.

Fixed effects in this model included for each node an individual intercept (0 + node) and an individual slope for NSH ratio or NSD ratio (node:ratio). Random effects included a random intercept for each node for cow nested within pen (0 + node|pen/cow) to account for multiple observations of the same cow and the potential effects of pen affiliation. Furthermore, a random intercept for week (0 + node|week) was included for each node. Lastly, a random intercept for the observation (1|obs) was included to ensure that the binary responses at the six nodes belonging to the same rising event shared the same variance and were not treated as independent observations. For a detailed discussion of data encoding and model formulation for IRTree GLMMs, see López-Sepulcre et al. (2015).

3 Results

3.1 Experiment 1: Neck strap height relative to cow wither height

3.1.1 Rising and lying down behaviours

In Experiment 1, we analysed 1409 rising events (mean ± SD: 35 ± 2.0 per cow) and 1405 lying down events (mean ± SD: 35 ± 1.9 per cow; Supplemental Table S1). None of the rising events were horse-like and 5 (0.4%) rising events were interrupted. Neither dog-sitting nor interrupted lying down events were observed. We did not statistically analyse these rare atypical behaviours further. The results of the GLMMs with the other atypical rising and lying down behaviours as responses are shown in Fig. 3 (random effect variance components in Supplemental Table S2). The odds that cows crawl backwards during rising decreased by a factor of 0.59 for a 0.1 increase in NSH ratio (95% CI: 0.43–0.79; Fig. 3B). The estimated probability of crawling backwards was never >0.05 (Fig. 3A). We found no statistical support for an effect of NSH ratio on the odds that cows perform a staggered head lunge or a sideways head lunge during rising. We also found no statistical support for an effect of NSH ratio on the odds that cows perform extensive inspection, repeated stepping, or pawing prior to lying down.

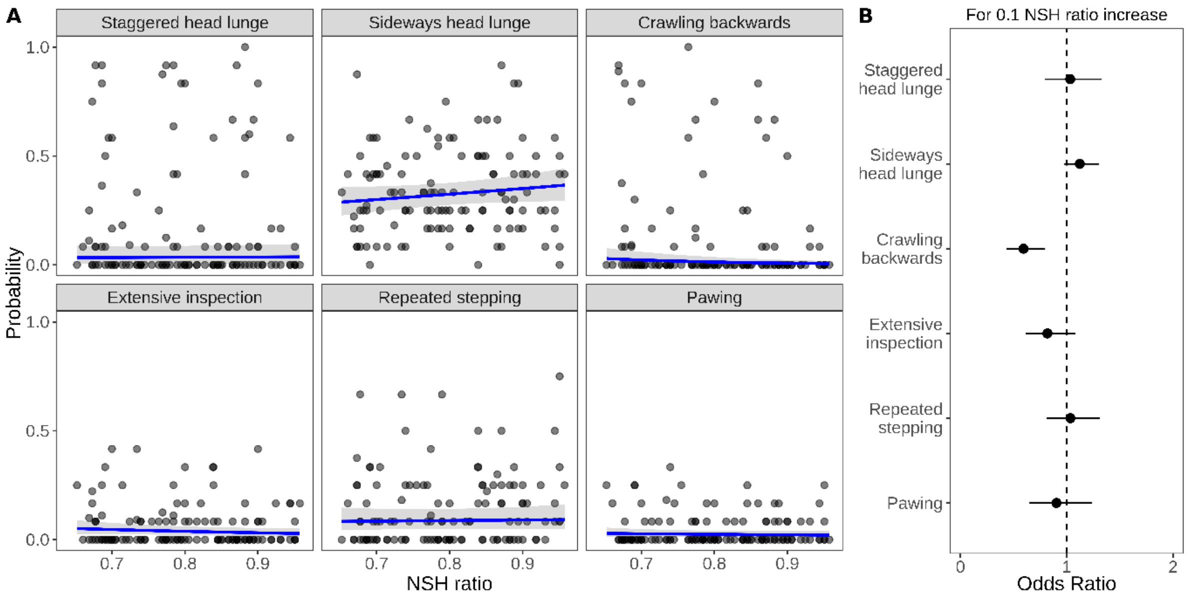

Figure 3. (A) GLMM estimated probabilities (solid line) with 95% CI (shaded area) for atypical behaviours during rising and lying down in dependence of NSH ratio (population level, considering only fixed effects). Points represent observed proportions for individual cows (please note that model estimates are based on non-aggregated observations taking into account potential cow, pen, and week effects). (B) Odds ratios with 95% CI for a 0.1 increase in NSH ratio. A significant effect at the 0.05 level is indicated when the 95% CI of the odds ratio does not include 1. Abbreviations: GLMM = generalised linear mixed effects model; CI = 95% quantile confidence interval; NSH = neck strap height.

3.1.2 General lying behaviour

In Experiment 1, cows were lying for 11.6 ± 2.02 h/day, divided into 11 ± 2.6 bouts with a mean duration of 66 ± 14.2 min (mean ± SD). The results of the LMMs with measures of general lying behaviour as responses are shown in Fig. 4 (random effect variance components in Supplemental Table S3). We found no statistical support for an effect of NSH ratio on daily lying time, lying frequency, or mean lying bout duration (Fig. 4D).

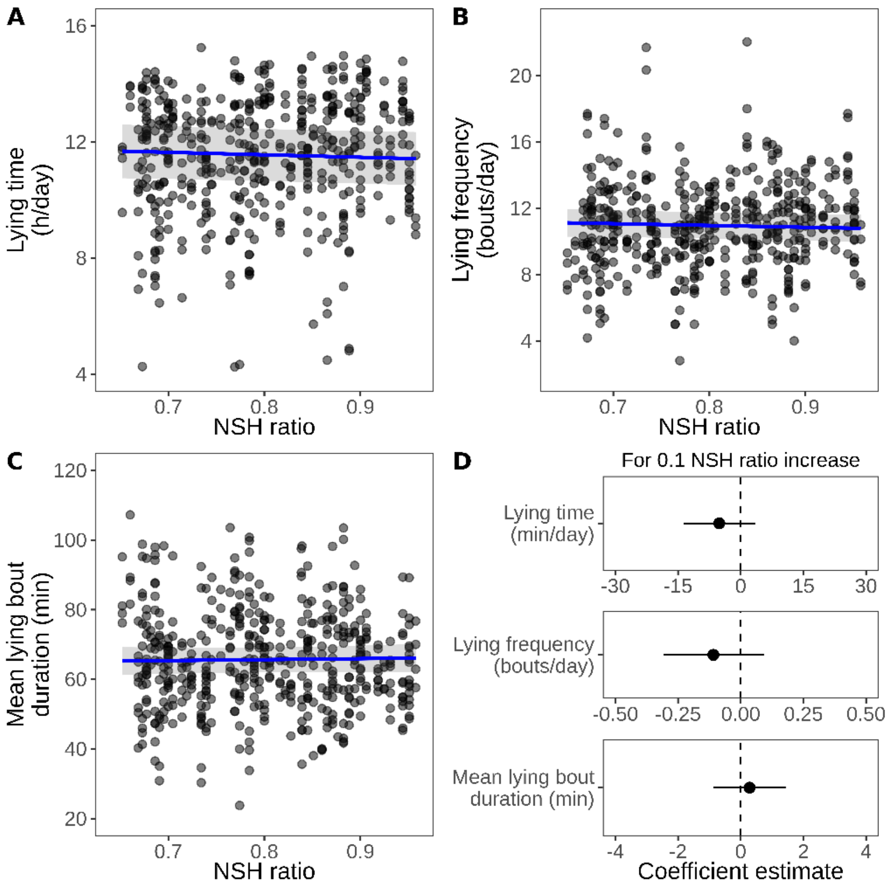

Figure 4. LMM estimates (solid line) with 95% CI (shaded area) for measures of general lying behaviour (population level, considering only fixed effects): (A) daily lying time, (B) lying frequency, and (C) mean lying bout duration in dependence of NSH ratio. Points represent observations for individual cows (please note that model estimates take into account potential cow, pen, and week effects). (D) Coefficient estimates for a 0.1 increase in NSH ratio. A significant effect at the 0.05 level is indicated when the 95% CI of the coefficient estimate does not include 0. Abbreviations: LMM = linear mixed effects model; CI = 95% quantile confidence interval; NSH = neck strap height.

3.2.2 Defecation behaviour around rising events

Of the 1409 rising events analysed in Experiment 1, cows defecated 249 (17.7%) times and urinated 41 (2.9%; not statistically analysed) times within the 120 s time window around the rising event while in the lying cubicle. The results of the GLMMs with faeces landing in the lying cubicle around rising events as responses are shown in Fig. 5 (random effect variance components in Supplemental Table S4). When considering all rising events, we found no statistical support for an effect of NSH ratio on the odds that faeces land in the lying cubicle (odds ratio: 1.39; 95% CI: 0.90–2.20; Fig. 5A). When considering only rising events involving a defecation while in the lying cubicle, the odds that faeces land in the cubicle increased by a factor of 2.16 for a 0.1 increase in NSH ratio (95% CI: 1.47–3.43; Fig. 5B). The results of the IRTree model are shown in Fig. 6 (random effect variance components in Supplemental Table S5). For defecations shortly after rising events while still in the lying cubicle, a 0.1 increase in NSH ratio increased the odds for cows to stand with all four hooves in the cubicle in the cubicle (Node 3) by a factor of 2.26 (95% CI: 1.18–5.86). For defecations of lying cows shortly before rising, a 0.1 increase in NSH ratio increased the odds for faeces to land in the lying cubicle (Node 4) by a factor of 2.54 (95% CI: 1.38–5.85). For defecations of cows standing with all four hooves in the lying cubicle shortly after rising, a 0.1 increase in NSH ratio increased the odds for faeces to land in the cubicle (Node 5) by a factor of 3.25 (95% CI: 1.25–16.85). We found no statistical support for an effect of NSH ratio on the odds that cows defecate around rising (Node 1) or the odds that cows are standing compared to lying when defecating around rising (Node 2).

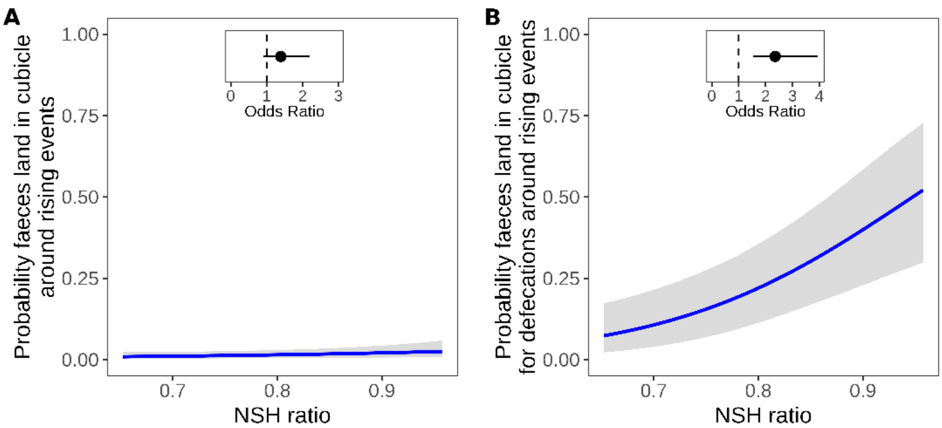

Figure 5. GLMM estimated probabilities (solid line) with 95% CI (shaded area) of (A) faeces landing in the lying cubicle around rising events in dependence of NSH ratio, and of (B) faeces landing in the lying cubicle if a cow defecates around rising while in the cubicle in dependence of NSH ratio. Odds ratios with 95% CI are shown for a 0.1 increase in NSH ratio. A significant effect at the 0.05 level is indicated when the 95% CI of the odds ratio does not include 1. Abbreviations: GLMM = generalised linear mixed effects model; CI = 95% quantile confidence interval; NSH = neck strap height.

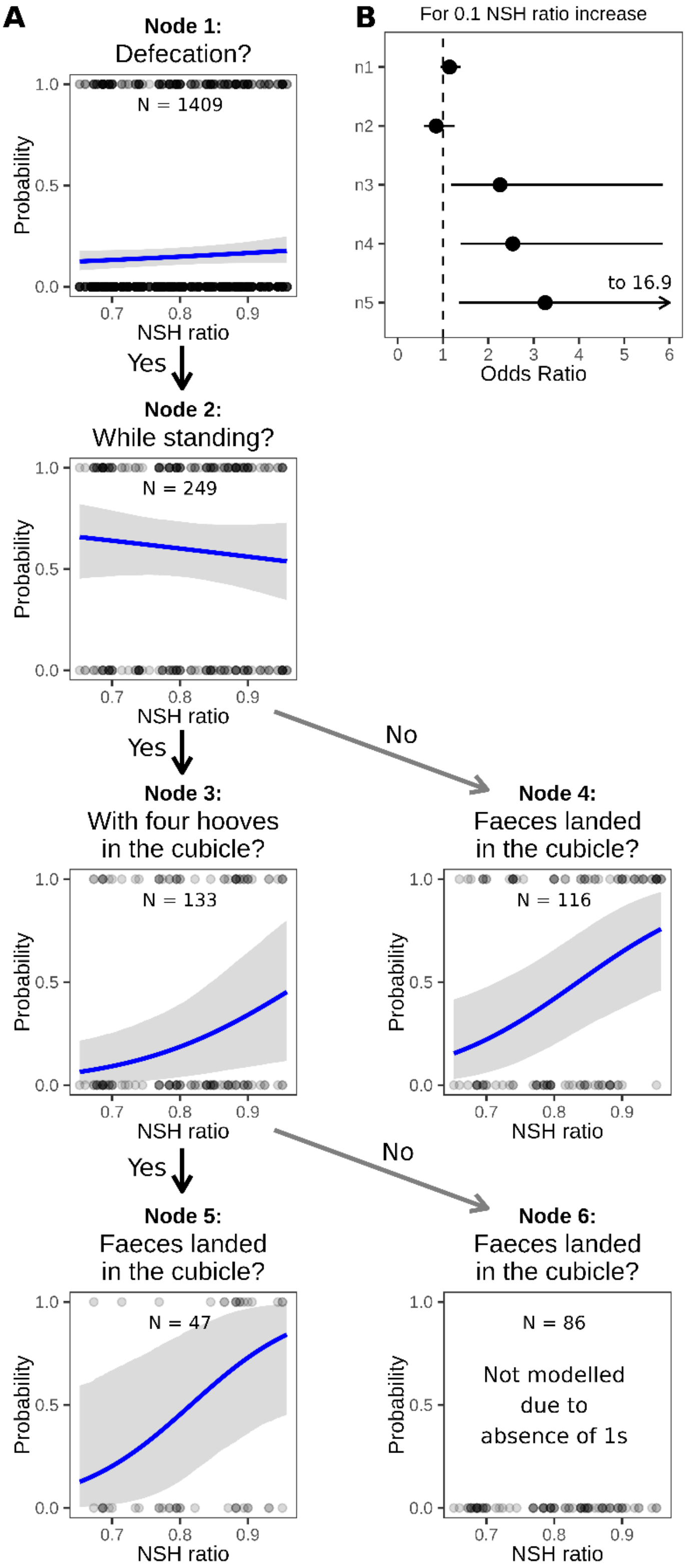

Figure 6. (A) IRTree GLMM estimated probabilities (solid line) with 95% CI (shaded area) for the individual nodes of the IRTree in dependence of NSH ratio. Points represent individual observations. N represents the number of observations at each node. Node 6 was not modelled as faeces never landed in the lying cubicle if a cow defecated around rising while standing with only the front hooves in the cubicle. (B) Odds ratios with 95% CI for a 0.1 increase in NSH ratio. A significant effect at the 0.05 level is indicated when the 95% CI of the odds ratio does not include 1. Abbreviations: IRTree = Item Response Tree; GLMM = generalised linear mixed effects model; CI = 95% quantile confidence interval; NSH = neck strap height.

3.2 Experiment 2: Neck strap distance from the curb relative to cow diagonal body length

3.2.1 Atypical rising and lying down behaviours

In Experiment 2, we analysed 947 rising events (mean ± SD = 24 ± 1.1 per cow) and 954 lying down events (mean ± SD = 24 ± 0.7 per cow; Supplemental Table 1). None of the rising events was horse-like, and 1 (0.1%) rising event was interrupted. We also never observed dog-sitting or interrupted lying down events. We did not statistically analyse these rare atypical behaviours further. The results of the GLMMs with the other atypical rising and lying down behaviours as responses are shown in Fig. 7 (random effect variance components in Supplemental Table S6). We found no statistical support for an effect of NSD ratio on the odds that cows perform a staggered head lunge, a sideways head lunge, or crawling backwards during rising (Fig. 7B). We also found no statistical support for an effect of NSD ratio on the odds that cows perform extensive inspection, repeated stepping, or pawing prior to lying down.

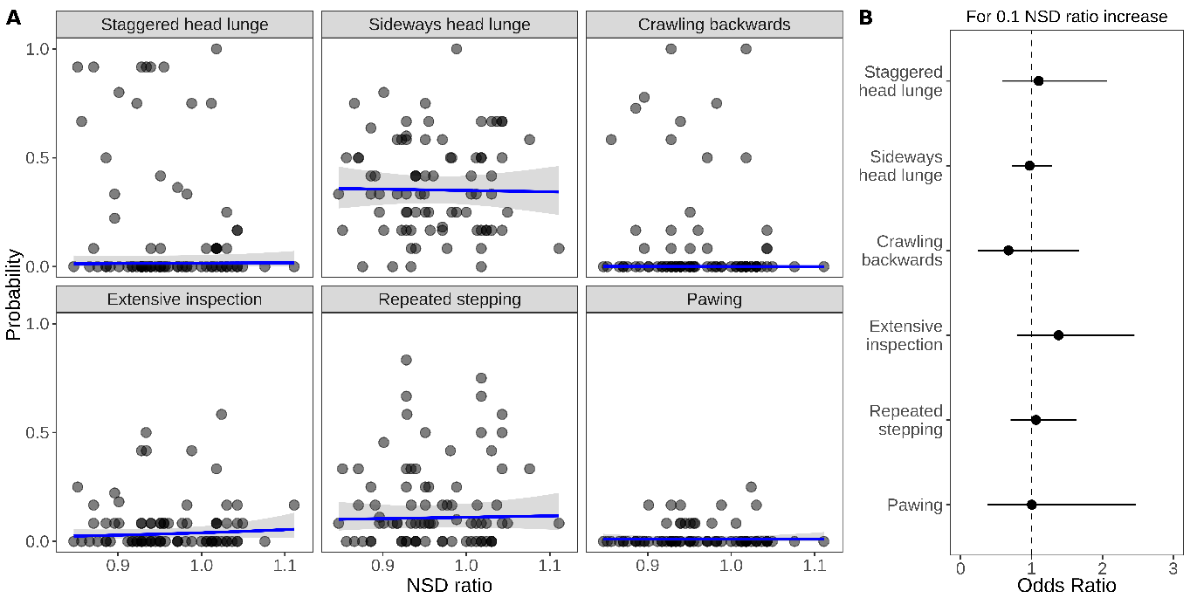

Figure 7. (A) GLMM estimated probabilities (solid line) with 95% CI (shaded area) for atypical behaviours during rising and lying down in dependence of NSD ratio (population level, considering only fixed effects). Points represent observed proportions for individual cows (please note that model estimates are based on non-aggregated observations taking into account potential cow, pen, and week effects). (B) Odds ratios with 95% CI for a 0.1 increase in NSD ratio. A significant effect at the 0.05 level is indicated when the 95% CI of the odds ratio does not include 1. Abbreviations: GLMM = generalised linear mixed effects model; CI = 95% quantile confidence interval; NSD = neck strap distance from the curb.

3.2.2 General lying behavior

In Experiment 2, cows were lying for 12.2 ± 1.66 h/day, divided into 11 ± 2.3 bouts with a mean duration of 69 ± 13.9 min (mean ± SD). The results of the LMMs with measures of general lying behaviour as responses are shown in Fig. 8 (random effect variance components in Supplemental Table S7). We found no statistical support for an effect of NSD ratio on daily lying time, lying frequency, or mean lying bout duration (Fig. 8D).

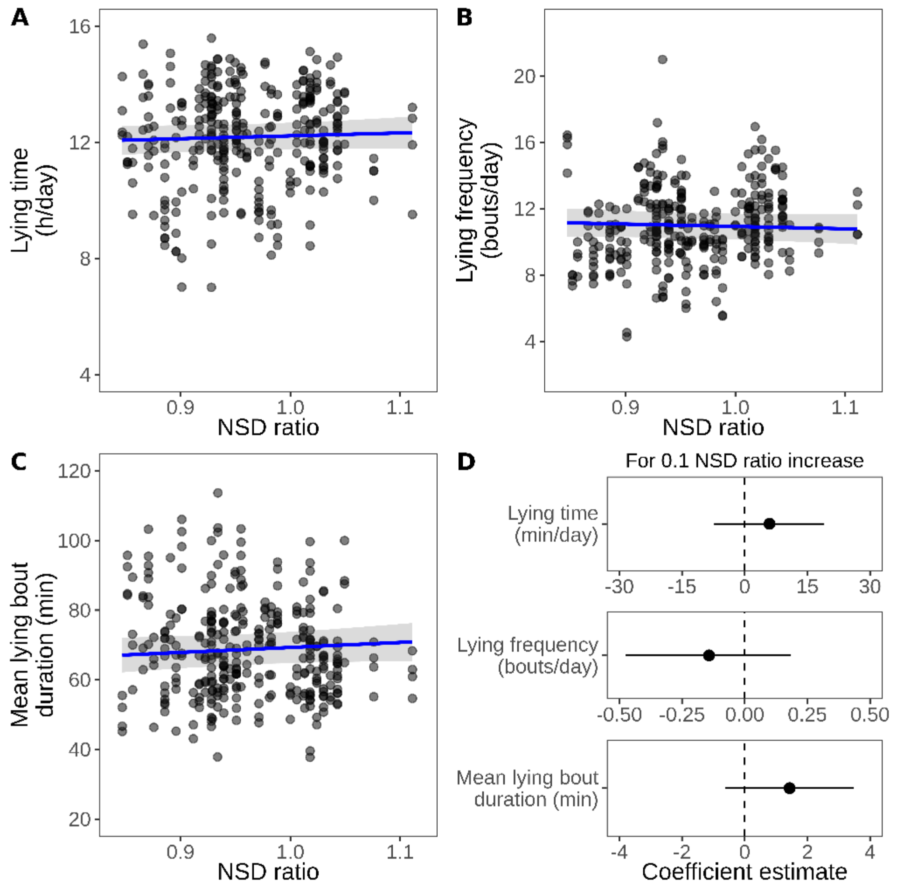

Figure 8. LMM estimates (solid line) with 95% CI (shaded area) for measures of general lying behaviour (population level, considering only fixed effects): (A) daily lying time, (B) lying frequency, and (C) mean lying bout duration in dependence of NSD ratio. Points observations for individual cows (please note that model estimates take into account potential cow, pen, and week effects). (D) Coefficient estimates for a 0.1 increase in NSD ratio. A significant effect at the 0.05 level is indicated when the 95% CI of the coefficient estimate does not include 0. Abbreviations: LMM = linear mixed effects model; CI = 95% quantile confidence interval; NSD = neck strap distance from the curb.

3.2.3 Defecation behaviour around rising events

Of the 947 rising events analysed in Experiment 2, cows defecated 197 (20.8%) times and urinated 32 (3.4%; not statistically analysed) times within the 120 s time window around the rising event while in the lying cubicle. The results of the GLMMs with faeces landing in the lying cubicle around rising events as responses are shown in Fig. 9 (random effect variance components in Supplemental Table S8). For all rising events, the odds that faeces land in the lying cubicle increased by a factor of 2.18 for a 0.1 increase in NSD ratio, although with weak statistical support (95% CI: 0.98–5.54; Fig. 9A). When considering only rising events involving a defecation while in the lying cubicle, the odds that faeces land in the cubicle increased by a factor of 2.44 for a 0.1 increase in NSD ratio (95% CI: 1.11–6.07; Fig. 9B). The results of the IRTree model are shown in Fig. 10 (random effect variance components in Supplemental Table S9). For defecations of lying cows shortly before rising, a 0.1 increase in NSD ratio increased the odds for faeces to land in the lying cubicle (Node 4) by 5.07 (95% CI: 2.23–22.10). We found no statistical support for an effect of NSD ratio on the other nodes of the IRTree.

Appendix III

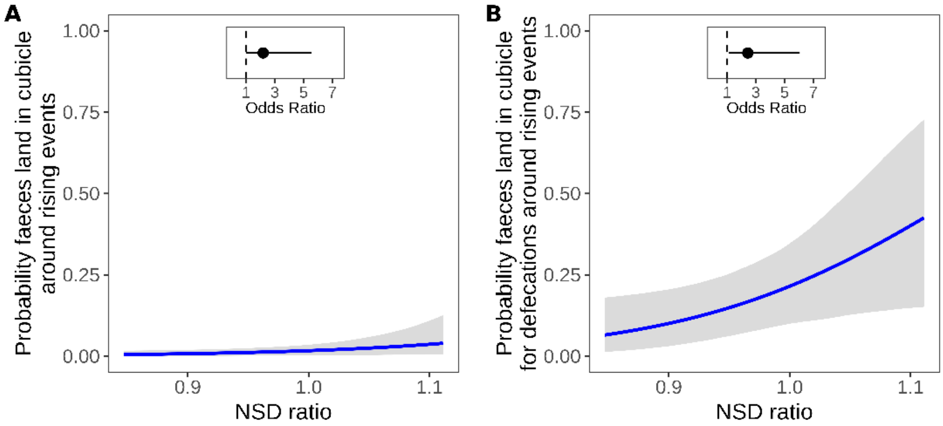

Figure 9. GLMM estimated probability (solid line) with 95% CI (shaded area) of (A) faeces landing in the lying cubicle around rising events in dependence of NSD ratio, and of (B) faeces landing in the lying cubicle if a cow defecates around rising while in the cubicle in dependence of NSD ratio. Odds ratios with 95% CI are shown for a 0.1 increase in NSD ratio. A significant effect at the 0.05 level is indicated when the 95% CI of the odds ratio does not include 1. Abbreviations: GLMM = generalised linear mixed effects model; CI = 95% quantile confidence interval; NSD = neck strap distance from the curb.

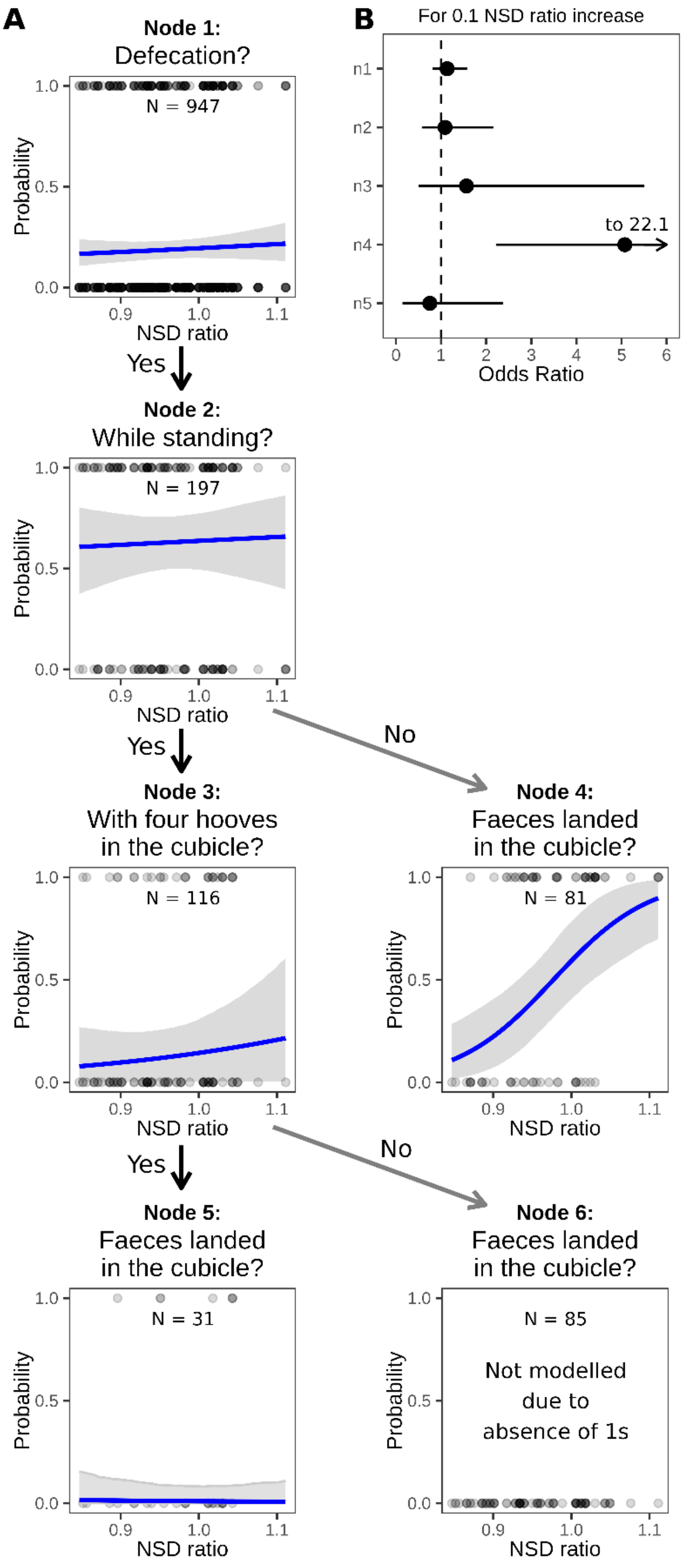

Figure 10. (A) IRTree GLMM estimated probabilities (solid line) with 95% CI (shaded area) for the individual nodes of the IRTree in dependence of NSD ratio. Points represent individual observations. N represents the number of observations at each node. Node 6 was not modelled as faeces never landed in the lying cubicle if a cow defecated around rising while standing with only the front hooves in the cubicle. (B) Odds ratios with 95% CI for a 0.1 increase in NSD ratio. A significant effect at the 0.05 level is indicated when the 95% CI of the odds ratio does not include 1. Abbreviations: IRTree = Item Response Tree; GLMM = generalised linear mixed effects model; CI = 95% quantile confidence interval; NSD = neck strap distance from the curb.

4 Discussion

We investigated the effects of neck strap positioning relative to cow body size on atypical rising and lying down behaviours, general lying behaviour, and defecation behaviour around rising events. In both experiments, all but one of the investigated atypical rising and lying down behaviours were rare, and we generally found no statistical support for an effect of neck strap positioning relative to cow body size on their prevalence. This suggests that cows were typically able to rise without excessive difficulty and rarely displayed signs of hesitance defined as atypical in our ethogram prior to lying down. Our results indicate that positioning of flexible neck straps relative to cow body size, as investigated in this study, does not markedly affect the movements of dairy cows during rising and lying down. This may be because the flexibility of the neck strap does not cause an abrupt cessation of movement upon collision.

The only atypical behaviour frequently observed was sideways head lunging. However, no statistical support was found for an effect of neck strap positioning relative to cow body size on its prevalence. Sideways head lunging is likely more related to the available forward space in lying cubicles (Veissier et al., 2004; Brouwers et al., 2024). Crawling backwards on the carpal joints was the only atypical behaviour affected by neck strap positioning, with a higher NSH ratio (neck strap height relative to cow wither height) decreasing the odds of this behaviour. Crawling backwards can cause skin abrasions and places excessive stress on the carpal joints due to the weight resting on them. Therefore, the design of lying cubicles should aim to minimise the occurrence of this behaviour. The estimated probability of crawling backwards was 0.05 at the most restrictive NSH ratio and decreased to even lower probabilities for higher NSH ratios, reaching near 0 probabilities at an NSH ratio >0.75. Interestingly, crawling backwards was a highly individual behaviour with only 5 of the 40 cows accounting for almost 80% of the observed occurrences. All of these cows had above average wither heights (ranging from 150 to 157 cm). Thus, our observations suggest that, despite the flexibility of the neck strap, some of the larger cows in our study did not have sufficient upward space to lift the front of their bodies or attempted to reduce contact with the neck strap and moved backwards in the lying cubicle while rising by crawling backwards on the carpal joints.

Regarding general lying behaviour, we found no statistical support for an effect of neck strap positioning relative to cow body size on lying frequency. As we also found no effects on atypical rising behaviours, this may indicate that neck strap positioning relative to cow body size, as included in the current study, did not affect the willingness of cows to transition between standing and lying. By contrast, Bernardi et al. (2009) found that restrictive neck rail positioning was associated with a reduced number of lying bouts, presumably because the neck rail interfered with rising and lying down. However, these authors investigated rigid neck rails, not flexible neck straps, and although the height of 118 cm was similar to that in this study, they tested them at 130 and 190 cm from the curb, which are more extreme compared to the positions in our study. Similar to lying frequency, we found no statistical support for an effect of neck strap positioning relative to cow body size on daily lying time or mean lying bout duration. This result is consistent with studies of neck rail placement that also reported no effect of neck rail position on lying time (Fregonesi et al., 2009; Tucker et al., 2005).

The average probability of a cow defecating shortly before or shortly after rising while still in the cubicle was 0.17 (Node 1 of the IRTree). This probability is consistent with the findings of Fregonesi et al. (2009), who also reported that defecation in lying cubicles was relatively rare and suggested that this may indicate that cows exited the cubicles quickly after rising, as cows defecate approximately 15 times per day (reviewed in Tonooka et al., 2022). If a cow defecated around rising while in the lying cubicle, the estimated probability of faeces landing in the cubicle was approximately 0.10 for an NSH ratio of 0.7. However, an increase of 0.1 in NSH ratio was associated with a more than twofold increase in the odds. Thus, the lowest NSH ratio in our study of 0.7 was the most effective in positioning cows in the lying cubicle in such a way that limits soiling of the bedding and that higher neck strap positions may decrease cubicle cleanliness.

For defecations around rising events, the estimated probability that a cow was standing compared to lying at the start of the defecation (Node 2 of the IRTree) was around 0.60. Neck strap positioning relative to cow body size did not affect this probability. Cows on pasture do not tend to defecate while in a lying position (Whistance et al., 2011), suggesting that they rise to defecate when movement space is not restricted (i.e., in open environments). Our findings may indicate that cows that felt the need to defecate were able to rise before defecating in the majority of cases. In studies where defecation behaviour was continuously monitored, Tucker et al. (2005) and Fregonesi et al. (2009) found that 69% and 55%, respectively, of defecations from cows in lying cubicles with neck rails were from lying cows, which would correspond to 31% and 45% of defecations being from standing cows. However, as we only analysed defecations around successful rising events, these numbers cannot be compared directly to our results as it is possible that cows also defecated while lying without rising shortly afterwards.

For defecations shortly after rising, a higher NSH ratio was associated with a higher probability of cows standing with all four hooves in the lying cubicle compared to standing with only the front hooves in the cubicle (Node 3 of the IRTree). This is consistent with Tucker et al. (2005) who reported an increase in time spent standing with all four hooves in the lying cubicle with higher neck rail placement, presumably because cows find this more comfortable than standing partially in the cubicle. Moreover, Bernardi et al. (2009) linked the ability to stand fully in the lying cubicle to a reduced risk of lameness and hoof disease, highlighting its importance for cow health. For defecations of cows standing with all four hooves in the lying cubicle shortly after rising, the probability of faeces landing in the cubicle (Node 5 of the IRTree) was low for NSH ratios of around 0.7, but increased with higher NSH ratios. This indicates that an appropriately positioned neck strap can accommodate both smaller and larger cows. Smaller cows can stand fully in the lying cubicle without touching the strap, while larger cows can stand fully in the cubicle by slightly stretching the strap. Although smaller cows might stand further forward than desired, this behaviour is likely discouraged because pressing against the neck strap is presumed to be somewhat uncomfortable. For defecations of lying cows shortly before rising, the probability of faeces landing in the lying cubicle (Node 4 of the IRTree) was also positively associated with NSH ratio. This may indicate that cows were not only standing but also lying further forward in the lying cubicles. Cows may have positioned themselves further forward when lying down to ensure that they did not lie on the curb and that their bodies were fully supported by the bedded area (Fregonesi et al., 2009).

A higher NSD ratio (neck strap distance from the curb relative to cow diagonal body length) was also positively associated with the probability of faeces landing in the lying cubicle for defecations around rising events. However, we only found this effect for defecations from lying cows (Node 4 of the IRTree) and not for standing cows (Node 3 multiplied with Node 5 in IRTree; Supplemental Fig. 1). This suggests that the distance of the neck strap from the curb is important in guiding cows when lying down, thereby affecting lying cubicle hygiene. In contrast to our results regarding standing cows, Tucker et al. (2005) and Fregonesi et al. (2009) both reported that when standing cows defecated, more of the defecations landed in the lying cubicle when the neck rail was positioned further from the curb. It is plausible that we did not find statistical support for such an effect because of the difference between neck rails and neck straps, because of our smaller range of positions compared to the above-mentioned studies (130–195 cm in Fregonesi et al., 2009; 140–233 cm in Tucker et al., 2005), or because we are lacking the statistical power.

In preliminary experiments, we also investigated the neck strap at 195 cm from the curb (mean NSD radio of the herd: 1.15). However, with this NSD, cows were frequently observed stepping into the lunge space. Furthermore, even with the neck strap closer to the curb, cows were occasionally observed to step into the lunge space with one or both front legs after rising (not systematically recorded). This may indicate that the cows were motivated to step forward after rising, which is in line with their natural rising movement sequence (Lidfors, 1989) but typically discouraged by the neck rail. On two occasions (with NSH ratios of 0.84 and 0.95, respectively), a cow walked completely into the lunge space. In both cases the cow was able to exit the lunge space again on her own without help from the farm staff. Stepping into the lunge space may be prevented by placing the front rail lower and closer to the brisket board to provide a better barrier to prevent cows from walking through (van Eerdenburg & Ruud, 2021). We placed the front rail at a height of 1 m to ensure that it did not interfere with the head lunge movement. However, the use of front straps made of flexible material, as done by Wilson et al. (2022), may be a more appropriate method of preventing cows from walking through the lying cubicle without considerably impeding head lunging.

Conclusion

Our study indicates that the positioning of flexible neck straps relative to cow body size, as tested in this study, does not considerably affect the rising and lying down movements of dairy cows. The flexibility of the neck strap appeared to accommodate cows of different sizes and minimise the impediment of movement. Lying cubicle soiling around rising events decreased with lower neck strap height relative to cow wither height and shorter neck strap distance from the curb relative to cow diagonal body length. We conclude that flexible neck straps can be a viable alternative to rigid neck rails by limiting the probability of defecation in lying cubicles around rising events without considerably impeding dairy cow movements during rising and lying down.

Ethics statement

Ethical approval for the study was obtained from the Veterinary Office of the Canton Thurgau, Switzerland (TG03/2021, Approval No. 33448).

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Curriculum Vitae

Scientific Contributions

Publications

Brouwers, S. P., Simmler, M., Savary, P., and Scriba, M. F. (2023). Towards a novel method for detecting atypical lying down and standing up behaviors in dairy cows using accelerometers and machine learning. *Smart Agricultural Technology*, *4*, 100199.

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Conference contributions

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