Estimation of dairy heifer body weight using 3D computer vision

- A precision livestock farming approach to youngstock management

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Swedish University of Agricultural Sciences, SLU
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Abstract

Youngstock plays a crucial role within dairy operations as the next generation of milking cows. Despite this, the cost of rearing youngstock and the impact of rearing management on growth trajectories and associated reproductive and production performance of replacement heifers are often overlooked. This is partly due to the challenges in efficiently and effectively monitoring youngstock performance throughout rearing. This thesis aimed to validate the concept that the body weight of developing dairy heifers (5 to 20 months) can be accurately estimated through the application of 3D computer vision technology. The hypothesis is that an overhead rearview image can provide sufficient information to extract adequate body measurements for development of an accurate BW estimation model. Thereby enabling timely monitoring and management of youngstock, leading to more cost-effective management and improved health, production, and reproductive performance in future dairy cows.

The study was conducted at the Swedish Livestock Research Centre in Uppsala, Sweden, over a period of four months starting in January 2024. Data was collected on four occasions, on 101 diary heifers of two breeds: Swedish Red (n = 59) and Swedish Holstein (n = 42). The collected data included body weights, 3D images, three manual metric body measurements (hip ischial width, hip height, and external hip joint width), and manual body condition scores for heifers aged ≥ 13 months.

The body measurements were manually acquired as reference values and extracted through photogrammetry applied to 3D time-of-flight imaging. These images were acquired directly after the heifer exited the weighing scale, with an overhead caudal rear view. Pearson correlations showed strong correlations between body weights from the scale and reference body measurements: hip ischial width (r = 0.94), hip height (r = 0.88), and hipometer (r = 0.88). Age in months also showed strong correlations (r = 0.93), while body condition score was weakly correlated (r = 0.27). Model training input features were age and 3D image extracted hip ischial width, hip height, and hip width measures, whereof hip width have been established to have a strong correlation to BW in other research (r = 0.75). Model training was performed with Gradient Boosting and Group K-Fold cross-validation, achieving a regression score of 0.93 (± 0.02) between estimated and reference body weights. The relative error across all 101 heifers was 5.35 % (± 0.51 %) with a relative mean square error of 26.0 kg (± 2.5 kg).

This thesis validated the possibility of accurately estimating body weight in developing dairy heifers using 3D computer vision, indicating the potential for further model enhancement and utilization to advance precision livestock farming (PLF) technology.

Keywords: body condition scoring, body measurement, body weight, computer vision, growth rate, precision livestock farming, time-of-flight, three-dimensional imaging, heifer, youngstock management

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Abbreviations

AFC	Age at first calving
BM	Body measurement
BW	Body weight
CG	Compensatory growth
CV	Computer vision
HH	Hip height
Hipin	Hip ischial width
HJW	Hip joint width
HW	Hip width
ID	Identification number
PLF	Precision livestock farming
RE	Relative error
RMSE	Root mean square error
SH	Swedish Holstein
SRB	Swedish Red
TOF	Time-of-Flight
2D	Two-dimensional
3D	Three-dimensional

1. Introduction

Monitoring livestock performance and implementing timely management adaptations require measurable parameters (Nir et al. 2018; Wang et al. 2023). However, for youngstock, rearing costs, investment returns, and performance data are comparatively invisible to the immediate productivity and robust performance records of the milking herd (Palczynski et al. 2022; Doidge et al. 2024). Given the limited financial resources in dairy operations, this often results in the marginalization of youngstock in management and investment decisions (Palczynski et al. 2022). This underscores the need for more efficient and effective technical support in youngstock management to improve performance monitoring, contributing to better heifer-rearing management and promoting the long-term sustainability of dairy operations (Palczynski et al. 2022; Wang et al. 2023).

Body weight (BW) is a valuable metric that provides insights into growth rates, body condition score (BCS), and overall animal health in response to rearing management (Hoffman 2007; Brown et al. 2014; Kashiha et al. 2014). As one of the few metrics offering such comprehensive information, BW monitoring empowers dairy farmers to make informed management decisions to promote benchmark values associated with enhanced herd health, reproductive and productive performance, ultimately leading to more profitable operations (Heinrichs et al. 2007). Benchmark values are typically based on breed standard target weights (Svensk Mjölk 2006) or as target percentages of mature BW (Troccon 1993; Blackwell et al. 2017; Växa 2022) to ensure favourable BW gains and growth rates. Estimations of mature BW, derived from mature cows within the herd, are advantageous as they account for farm-level selection and genetic variations (Hoffman 2007; Bach & Ahedo 2008). Frequent precision monitoring of BW within the herd thereby poses to further improve estimations for favourable benchmark values for individual animals.

Manual BW monitoring by calibrated scales, although offering high accuracy, poses challenges for farmers. Such as limited access, substantial investments, and the laborious and time-consuming nature of weighing and relocating animals (Heinrichs et al. 2007; Wangchuk et al. 2018). Body measurements (BM) and BCS are further manual approaches providing indirect estimations of cattle BW, but they also have their limitations. While requiring less costly equipment, they often require increased labor, close animal handling, and substantial time investment. Thereby raising the economic investments, risk of human injury and animal stress, and thus posing welfare concerns (Heinrichs et al. 1992, 2007; Guo et al. 2017; Martins et al. 2020). These challenges result in sporadic measurements susceptible to interand intra-assessor variations (Hansen et al. 2018; Martins et al. 2020), limiting the reliability of timely management adjustments. The challenges are especially acute in youngstock rearing, where a “reactive treatment” approach due to insufficient technical assistance is common (Palczynski et al. 2022). Precision livestock farming (PLF), particularly three-dimensional (3D) computer vision (CV), offers an alternative to the manual monitoring of youngstock (Song et al. 2014; Nir et al. 2018; Kamchen et al. 2021; Peng et al. 2024). However, these technologies require refinement for practical application (Lobo et al. 2019; Martins et al. 2020; Ruchay et al. 2020; Ahlberg 2024). PLF not only poses to circumvent the issues of manual approaches but also provides an opportunity for more frequent and precise individual-level management, offering a proactive approach to replacement heifer rearing in the face of increasing stock densities (Pezzuolo et al. 2018; Palczynski et al. 2022; Wang et al. 2023). The development and utilization of PLF are therefore increasingly important to enable timely monitoring and management of youngstock, leading to more cost-effective youngstock management and, consequently, an enhanced production and reproductive performance in future dairy cows. Current CV advancements within research and commercial technical solutions are mainly focused on mature dairy cattle, leaving a technical gap concerning youngstock.

This study aims to validate the concept that the BW of developing heifers can be accurately estimated through the application of 3D CV technology. The hypothesis is that an overhead rearview image can provide sufficient information to extract adequate body measurements for development of a model capable of accurately estimating the BW of growing heifers aged 5 to 20 months.

2. Literature Review

2.1 Growth

The BW of a heifer is subject to the interplay of growth and consequent alterations in body composition. The growth encompasses the development of structural tissues such as bone, muscle, and organs, coupled with accumulation of adipose tissues (Maynard & Loosli 1969). Due to varying onsets and pace of growth in these tissues, the body composition undergoes shifts as the heifers age. Furthermore, the expression of the inherited growth capacity is determined by genetics, management, and environmental factors (Simpfendorfer 1973; Heinrichs & Hargrove 1987), such as nutritional planes, housing, and sickness (Hoffman et al. 1994). Notably, heifer BW also fluctuates depending on time of day and from day-to-day. This BW fluctuation is due to differences in gut fill due to variations in feed and water intake, as well as excetion patterns and activity levels (Davis & Hathaway 1955; Enevoldsen & Kristensen 1997; Hoffman 1997).

During the initial 12 months of the heifer's life, skeletal growth primarily accounts for the increase in BW. By seven months of age, height increase attributed to long bone growth reaches 80 % of mature height, while only 35-45 % of mature weight is achieved at this age. At 12 months, long bone growth is slowed down due to puberty onset, having reached 90 % of mature height (Hammack & Gill 2009; Craig et al. 2016). As the maximum skeletal development occurs during the initial 12 months, the importance of optimal nutritional planes to prevent stunted skeletal development, which cannot be rectified at older ages, is underscored (Wathes et al. 2014; Craig et al. 2016). This is of particular importance for reproductive performance, as inadequate skeletal growth has been linked to an increased risk of dystocia as a result of disproportion between the pelvis and the size of the fetus (Wathes et al. 2014; Nogalski et al. 2024). Moreover, BW gains are recommended to align with skeletal development to mitigate adverse effects on reproductive and milk production potential (Heinrichs et al. 1992). By monitoring skeletal development using indicative body measurements, such as hip height (HH) and hip width (HW), tailored growth curves can be established, pinpointing deviations from recommended BW gains, i.e. under- and overconditioning (Enevoldsen & Kristensen 1997). Breed-specific benchmarks for these body measurements are available; for instance, Elanco Animal Health's (2004) *Body Condition Scoring for Replacement Heifers* offers standards for Holstein heifers in combination with recommendations for BW and BCS.

2.1.1 Compensatory growth

Tailored feeding regimes can effectively regulate heifer BW and growth rates. Induction of compensatory growth (CG) builds on the concept of intentionally restricting nutrition to trigger an accelerated growth rate when unrestricted feeding resumes. This approach aims to improve feed and growth efficiency, allowing animals to reach the same weight as if never undergone a period of reduced growth and nutrition (Hornick et al. 2000). For example, in dairy heifer rearing, this offers a simple, practical, and economical feeding regimen for animals not growing as expected for their age and breed (Park et al. 1987).

During periods of restricted growth rates the heifer body condition shifts towards a leaner condition accompanied by a reduction in body weight (Paquay et al. 1972; Hornick et al. 2000). During the compensatory phase, initiated by re-alimentation, the heifer body composition regains BW rapidly through accelerated growth (Wright & Russel 1991; Hornick et al. 2000). The accelerated tissue turnover deposition pattern differs with breed and age, typically progressing from viscera to muscle, and then adipose tissues (Wright & Russel 1991). Dairy breeds, however, exhibit a predisposition to adipose tissue deposition even at the onset of CG (Hornick et al. 2000) and have been linked to an increase in adiposity by CG (Wright & Russel 1991). Thus the risk of postpubertal adiposity increases, which has been linked to reduced reproductive (Heine et al. 2021) and milk production potential (Capuco et al. 1995; Macdonald et al. 2005; Meyer et al. 2006). Heine et al. (2021) pinpoints 15 months of age as an important timestamp to implement preventative measures, by consideration of nutritional planes, to avoid postpubertal adiposity in Holstein heifers.

2.2 Reproductive performance

The reproductive performance of heifers depends on nutrition, BW, body condition, breed, and genetics. Nutritional manipulation is recognized to play a significant role in regulating puberty onset, with the potential to either advance or delay onset by adjusting feed allowance; increasing dietary energy and protein to advance (i.e. high growth rate), or restricting to delay (i.e. low growth rate) (Buskirk et al. 1995; Gasser et al. 2006b; c; d). Therefore, age at puberty is inversely related to growth rates (Ferrell 1982), and consequently conception rates. Studies indicate that puberty occurs at critical BWs, with diverse ages between control and treatment groups, while the BW at puberty onset remains similar (Barash et al. 1994; Chelikani et al. 2003). The puberty onset occurs at 30-45 % of the estimated mature BW in dairy heifers (Van Amburgh et al. 1998; Heinrichs & Jones 2022). Additionally, body condition, particularly in the form of adipose and protein reserves, has been found to be comparable at puberty regardless of treatment, suggesting the importance of adequate tissue reserves for achieving puberty (Chelikani et al. 2003). The effect of nutritional manipulation has also been indicated to depend on timing. Showing that young heifers, at the ages between 4 and 6.5 months, are most receptive to nutritional manipulation for advanced pubertal onset. The effect is however, decreasing from 6 up to 9 months of age (Gasser et al. 2006a; Cardoso et al. 2014).

The prepubertal nutritional manipulation influences postpubertal reproductive performance through its effect on BW and body condition. Handcock et al. (2020) established positive curvilinear relationships between pre-breeding BWs and reproductive performance (calving and re-calving rates). Ferrell (1982) found similar relationships between BCS and conception rates. In addition, BW at calving has an established negative correlation with dystocia (Thompson et al. 1983; Erb et al. 1985), with reservations for excessive BW, BCS and postpubertal adiposity, that are associated with increased dystocia risk (Hoffman & Funk 1992; Hoffman et al. 1996; Heine et al. 2021). These findings underscore the adverse impact of underconditioned and overconditioned heifers on reproductive performances. Proper heifer frame size in relation to fetus size also plays a pivotal role, as inadequate skeletal growth in the pelvic region and greater fetus weights are linked to heightened dystocia risk (Nogalski et al. 2024).

To mitigate the risk of dystocia, the recommended age at first calving (AFC) falls within the range of 22 to 26 months (Simerl et al. 1991; Atashi et al. 2021), reflecting the estimated timeframe required for achieving adequate skeletal development without incurring excessive weight gains in heifer (and calf), and the associated higher BCS (Hoffman et al. 1996; Nogalski et al. 2024). This timeframe may also contribute to avoidance of low growth rates associated with delayed first insemination, and high growth rates that may negatively affect the conception rates (Brickell et al. 2009). Notably, optimal BWs and growth rates are breed and herd-specific i.e., influenced by genetic variance, differs with age (Hoffman & Funk 1992), and vary between production and feeding systems (Macdonald et al. 2005; Hayes et al. 2019).

2.3 Milk production potential

Mammary gland development is crucial for future milk production and progresses through three distinct growth phases; prepubertal allometric growth, peri-pubescent isometric growth, and post-breeding allometric growth (Macdonald et al. 2005). During the prepubertal phase (from 3 months to puberty onset) rapid growth rates have been suggested to induce excessive fat deposition in the mammary fat pad and reduce the growth of secretory tissue during allometric growth, thereby causing a detrimental effect on mammary development and subsequent milk production potential (Capuco et al. 1995; Sejrsen & Purup 1997; Van Amburgh et al. 1998; Sejrsen et al. 2000; Wathes et al. 2014). However, it is important to note that impaired mammary development rather seems to be a result of rapid growth rates due to high-energy diets resulting in higher adiposity accumulation, or genetic predisposition of higher adiposity, than the growth rate itself (Silva et al. 2002). As a result, adiposity, illustrated as high BCS, is shown to be a better predictor of impaired mammary development and subsequent milk production potential (Silva et al. 2002). For example, high BCS at first insemination has been associated with decreased milk production in the following lactation. Handcock et al. (2019b) identified a positive curvilinear relationship between heifer BW and milk production in the first three lactations. This suggests that lighter heifers, with a BW increase, often experience a boost in future milk production. At the same time, heavier heifers, irrespective of breed, generally show a greater potential for lifetime milk production. However, excessive overconditioning can undermine this advantage and should be managed carefully. Additionally, critical prepubertal growth rates have been identified as key to maintaining production potential, with no apparent limitations for postpubertal growth rates (Mourits et al. 2000).

When considering lifetime milk production, the trade-off between early calving and long-term productivity is to be considered (Svensson & Hultgren 2008; Eastham et al. 2018). The optimal AFC for a high lifetime milk production is suggested to be a combination of high BW without incurrence of excessive adiposity at an AFC between 22 and 25 months (Ettema & Santos 2004; Eastham et al. 2018). A lower AFC reduces milk production potential (Hoffman et al. 1996), suggested to be a result of inadequate mammary development (Ettema & Santos 2004), skeletal growth (Nogalski et al. 2024) and BW (Thompson et al. 1983; Erb et al. 1985). These factors also increase the risk for dystocia which is linked to reduced milk production potential in the first lactation (Eaglen et al. 2011).

2.4 Economy

The rearing of replacement heifers stands out as a significant cost consideration influencing the economic efficiency of a dairy operation, representing the second largest cost and accounting for up to an estimated 20 % of the total operational costs (Heinrichs 1993), as well as 13 % of the milk price (Nor et al. 2012). These costs are primarily driven by labor efficiency and feed expenses (Gabler et al. 2000). As the replacement dairy heifer turns profitable at the time of first calving (Gabler et al. 2000), AFC determines the investment duration of feed and labor without return. Moreover, as discussed earlier in the literature review, the effect of the rearing management on factors such as growth rate, skeletal development, BCS, and BW at critical stages of heifer rearing, as well as animal health, will affect the magnitude of the investment, as well as the future returns, through positively or negatively influencing the heifer and future cows' health, reproductive and milk production potential. By enabling efficient and effective monitoring of measurable metrics within youngstock rearing, detection and adaptations can be made in a timely manner for heifers to make profit for the dairy operation (Boulton et al. 2017).

2.5 Body weight estimation

2.5.1 Body weight estimations based on correlations

Body measurements (BM) offer an established approach for indirect evaluation of BW, growth (Heinrichs et al. 1992, 2007), and skeletal development in cattle (Enevoldsen & Kristensen 1997). Furthermore, BMs can be considered beneficial phenotypes associated with enhanced reproductive performance, herd health, and future milk production, and can favourably be promoted within the rearing management (Martins et al. 2020).

Estimating BW through BMs eliminates the need for costly equipment and reduces the laborious and time-consuming nature of weighing and relocating animals (Heinrichs et al. 2007; Wangchuk et al. 2018). The approach is further simplified by utilizing BMs with prominent anatomical landmarks, making them easily identifiable for farmers during measurements (Enevoldsen & Kristensen 1997). Based on the BM, calibrated tools (Dingwell et al. 2006) or equations (Heinrichs et al. 1992) BW can then be estimate through correlations. The heart girth tape and hipometer (i.e. external hip joint width (HJW)) are calibrated tools demonstrating high accuracy estimations for Holstein heifers aged 3 to 15 months (approx. 200 to 400 kg), although they exhibit limitations outside this range (Dingwell et al. 2006). The width between the hip and pin bone (Hipin), a newer BM, has demonstrated potential for estimating BW in Swedish Holstein (SH) and Swedish Red (SRB) heifers aged 6 to 19 months (174 to 575 kg), particularly for the SH breed (Ahlberg 2024). Other BMs strongly correlated to heifer BW include hip height (HH) (Song et al. 2014), wither height, hip width (HW), and body length, as seen in Table 1. All BMs, excluding heart girth, reflect skeletal growth without significant influence of adiposity, and should theoretically provide reliable benchmark values for growth (Heinrichs et al. 1992; Enevoldsen & Kristensen 1997; Dingwell et al. 2006).

Despite the benefits of applying these body measurements as monitoring tools, challenges persist due to their subjective, labor-intensive, and time-consuming nature. The majority of the tools also require training for consistency and close animal handling, leading to a heightened risk of human injury and animal stress, thus posing welfare concerns (Guo et al. 2017; Jabbar et al. 2017; Martins et al. 2020).

Table 1. Correlations between body weight (BW) and body measurements (BM) in previous studies; Ahlberg (2023)[A], Heinrichs et al. (1992)[B], Dingwell et al. (2006)[C], for Swedish Red (SRB) and Swedish Holstein (SH).

Body measurement	**Pearson correlation[A]**			**R^2**
	SRB+SH	*SRB*	*SH*	*SH*
Heart girth, cm	0.94	0.95	0.96	0.99 [B]
Heart girth, kg	0.94	0.95	0.96	0.94 [C]
Hipometer, kg	0.91	0.91	0.92	0.92 [C]
Hip ischial width, cm (Hipin)	0.82	0.80	0.85	
Hip height, cm (HH)	0.79	0.84	0.87	
Wither height, cm (WH)	0.75	0.83	0.84	0.96 [B]
Hip width, cm (HW)	0.75	0.76	0.73	0.98 [B]
Body length, cm (BL)	0.68	0.69	0.68	0.96 [B]

2.5.2 Automated body weight estimation

Advancements in PLF offer promising alternatives for continuous, consistent, remote, and non-invasive monitoring of individual animal BWs. The walk-over weighing (WOW) system is an automated unmanned version of the conventional scale weighing, where animals pass over a scale platform within the housing system to record BW. Despite the identified benefits of this system in youngstock rearing, environmental disruption remains a challenge, as well as risks of faulty recordings (Segerkvist et al. 2020). Instead, advances in CV systems offer promising alternatives (Wang et al. 2023) by utilizing vision in the form of two-dimensional (2D) and three-dimensional (3D) imaging in combination with machine learning (ML) to estimate BW from extracted BMs (Song et al. 2014; Tasdemir & Ozkan 2019; Martins et al. 2020; Le Cozler et al. 2022), body mass or surface area (Hansen et al. 2018; Nir et al. 2018; Kamchen et al. 2021; Le Cozler et al. 2022).

The time-of-flight (TOF) camera is an often applied 3D imaging sensor within cattle operations (Qiao et al. 2021), offering advantages in cost, accuracy, reliability, data collection, and compact size of the hardware in comparison to other alternatives on the market (He & Chen 2019). The TOF camera projects modulated light onto a scene, capturing the phase shift between the emitted and reflected light, and translates this information into depth (mm). By determining the depth of each pixel in view, a depth image (i.e. point cloud) providing detailed distance information can be generated (He & Chen 2019). For optimal image capturing the camera's noise sensitivity is to be taken into consideration. Noise sources shown to reduce image quality are high-velocity movements of objects (Salau et al. 2015), light reflectivity differences (due to fur color and texture) (Salau et al. 2015; Vázquez-Arellano et al. 2016), adverse weather conditions (rain, snow, mist, and dust), and natural light (Vázquez-Arellano et al. 2016; Ruchay et al. 2020). The measurement range (3 to 35 meters) and decreasing reliability in imaging objects at greater distances is also discussed by Vázquez-Arellano et al. (2016), Ruchay et al (2020), and Wang et al (2023).

The provided camera viewpoints determine the perspective of a 3D image and thereby define the assessable body regions. Additionally, a live animal exhibits non-rigid characteristics, meaning its shape varies with movement, and consequently, the utilized image processing technique is crucial for the accurate extraction of body measurements (Ruchay et al. 2020). Photogrammetry, a method identifying anatomical landmarks of objects on a digital image, was suggested by Tasdemir & Ozkan (2019), for the estimation of BW in dairy Holstein. The accuracy in their study was high ($R^2 = 0.995$). However, photogrammetry can be limited when anatomical landmarks aren't prominent, for example at high BCS (i.e. high fat deposition), when animals shift their stance (Song et al. 2014), when applied to young heifers (< 8 months) with incompletely developed skeletal structure (Pezzuolo et al. 2018; Lobo et al. 2019) or due to dark colored animals and inappropriate lighting (Gaudioso et al. 2014).

Previous studies within the field state that further improvement and automatization of 3D CV systems for BW estimations are needed before commercialization is possible. For example, reliable detection of anatomical landmarks and functional adoptions to farm management systems needs to be developed as well as evaluated in farm settings over time (Pezzuolo et al. 2018; He & Chen 2019; Martins et al. 2020; Ruchay et al. 2020; Ahlberg 2024).

2.6 Body condition scoring

Body condition scoring (BCS) is a commonly used method and one of the most important tools in dairy farming for the evaluation and monitoring of metabolic health in cattle. It provides valuable information to support and improve management decisions concerning herd nutrition, to enhance productivity, reproductivity, and overall herd health (Zin et al. 2020; Wang et al. 2023). It is a qualitative assessment of energy reserves in adipose tissues, independent of BW and body size, based on principal descriptors of specific body regions and palpation of fat deposits (Wildman et al. 1982; Edmonson et al. 1989; Ferguson et al. 1994). Thereby, BCS assessments can indicate deviations from recommended body conditions, i.e. under- or overconditioning, or rapid fluctuations, which can result in reduced fertility and milk yield, as well as indicate compromised health (Bewley & Schutz 2008).

Numerical score recommendations for heifers can be found from birth (Elanco Animal Health 2004; Heinrichs et al. 2023) and six months of age (Kellogg n.d.). Additionally, general textual descriptors and illustrations specified for U.S. Holstein heifers are available, with specifications at 12 and 24 months of age (Elanco Animal Health 2004). Consistent across the recommendations is the advice that dairy replacement heifers should generally score lower than mature cows, with a maximum score of BCS 3.5 on a five-point scale with 0.25 increments. Generally, heifers are advised to maintain a score of 2.0 to 2.5 until six months of age, followed by 2.5 to 3.0 until breeding age, and then gradually increasing to 3.5 at calving (Elanco Animal Health 2004; Heinrichs et al. 2023; Kellogg n.d.). While BCS assessments are standardized across all breeds, it is essential to consider that each breed has its distinct conformational characteristics (DairyNZ 2022). Additionally, recognition of the differentiating conformation of heifer skeletal structure and adipose reserves to mature dairy cattle is important for conducting accurate assessments (Elanco Animal Health 2004; Zin et al. 2020).

2.6.1 Manual body condition scoring

Manual assessments for BCS are laborious and time-consuming, even more so in large scale operations, thus scoring is often carried out less than optimal for timely management changes (Hansen et al. 2018; Zin et al. 2020). The scoring is further significantly affected by both intra- and inter-assessor variability. Experienced assessors have demonstrated high-quality assessments (Wilkins et al. 2015), yet due to the subjective nature and lack of quantifiability there is still a reduced sensitivity to subtle changes (Hansen et al. 2018). Wildman et al. (1982) determined that observers reached a consensus in their assessments approximately 58 to 67 % of the time, with discrepancies of ± 0.25 units occurring in the remaining cases.

2.6.2 Automated body condition scoring

Automated body condition scoring offers significant advantages in mitigating both intra- and inter-assessor variability, ensuring uniform, precise and readily accessible assessments across large herds (Bewley & Schutz 2008; Mullins et al. 2019). Moreover, it bypasses the labor-intensive and time-consuming nature of manual assessment (Wilkins et al. 2015). The 3D technology incorporated in automated BCS advantageously facilitates frame selection from continuous video sequences to achieve optimal scoring angles independent of animal movement (i.e. a non-rigid shape) (Mullins et al. 2019). The implementation of automated BCS and the frequent monitoring of dairy cows have underscored the potential benefits of CV. The extensive data gathered have enabled advancements in model development (Mullins et al. 2019; Zin et al. 2020; Hernandez-Gotelli et al. 2023), leading to a deeper understanding of BCS dynamics. Shedding light on important factors influencing BCS and their implications on performance variables (Truman et al. 2022; Hernandez-Gotelli et al. 2023).

3. Materials and Methods

3.1 General Aspects

The study was conducted at the Lövsta Swedish Livestock Research Centre, Uppsala, Sweden, between December and April of 2024. The centre stimulates Swedish conventional farms while offering a controlled environment with accessibility and routine procedures for the use of a weighing crush.

3.2 Animals and Housing

The study included a total of 101 heifers of the breeds Swedish Red (SRB) and Swedish Holstein (SH), aged 5 to 20 months. The recruitment of heifers was exclusively conducted internally, with a mean birth weight of 37.4 (min: 26.3; max: 52.7) kg. The heifers were housed in a non-insulated barn in a loose housing system subdivided into four units based on age and weight criteria. Each group had a different distribution of heifers throughout the study period, with the youngest heifers entering unit one, and as they aged and gained weight, progressed up to subsequent units, eventually reaching unit four housing the oldest heifers within the study. Upon relocation out of unit four, the heifers left the study. A detailed overview of the number of heifers per breed as well as number of new individuals involved in the study at each data collection can be found in Table 2 The heifers were provided with free access to fresh water and were fed silage *ad libitum,* as well as approximately 2 kg of concentrate feed per heifer and day in unit one.

Table 2. Overview of the distribution of heifers, breed, and age within the housing units at each data collection occasion, including new heifers entering the study (n).

Data Collection		**Unit**				Total
		1	**2**	**3**	**4**	
1	Nr of heifers	14	13	32	18	77
	Swedish Holstein	3	5	18	6	32
	Swedish Red	11	8	14	12	45
	Age, months	5 - 7	7 - 9	9 - 13	13 - 18	
2	Nr of heifers *(new)*	16 *(5)*	16	32	18	82
	Swedish Holstein	6	5	18	4	33
	Swedish Red	10	11	14	9	44
	Age, months	5 - 7	7 - 9	10 - 14	13 - 19	
3	Nr of heifers	16	10	28	21	75
	Swedish Holstein	6	2	17	9	34
	Swedish Red	10	8	11	12	41
	Age, months	5 - 8	7 - 9	9 - 13	13 - 19	
4	Nr of heifers *(new)*	22 *(7)*	9	30	21	82
	Swedish Holstein	8	2	18	6	34
	Swedish Red	14	7	12	10	43
	Age, months	5 - 8	7 - 9	9 - 13	13 - 20	
5	Nr of heifers	22	9	23	23	77
	Swedish Holstein	8	2	13	11	34
	Swedish Red	14	7	10	12	43
	Age, months	5 - 9	8 - 9	10 - 12	13 - 18	
6	Nr of heifers *(new)*	17 *(6)*	13	30	20	80
	Swedish Holstein	7	2	15	11	35
	Swedish Red	10	11	15	9	45
	Age, months	5 - 7	7 - 10	8 - 13	13 - 16	
7	Nr of heifers	17	9	26	25	77
	Swedish Holstein	7	2	10	14	33
	Swedish Red	10	7	16	11	44
	Age, months	5 - 7	8	8 - 12	13 - 17	
8	Nr of heifers *(new)*	17 *(6)*	15	26	16	74
	Swedish Holstein	7	5	10	10	32
	Swedish Red	10	10	16	6	42
	Age, months	5 - 7	7 - 9	9 – 13	13 - 17	

3.3 Study Design

Data were collected at 14 day intervals on eight occasions between January and April 2024, coinciding with the monthly weighing routine at the research centre every other time. The collected data included animal ID numbers, BW, 3D images (with possibility to extract 2D images), and manual BMs. Based on the heifer ID numbers, age, breed, birth weights were extracted from the locally utilized database after each data collection.

3.3.1 Body Weights and Image Data Collection

At each data collection, reference BWs were systematically collected for all heifers using an electronic cattle weighing crush (PM 2855) manufactured by Marechalle-Pesage Livestock in Chauny, France. The heifers entered the scale individually, with the exit gate secured to ensure their containment and the entrance gate closed behind them upon entry. The scale was fitted with an electronic identification (EID) reader that upon entry transmitted each heifers ID to a weighing indicator (TRU-Test EW6) connected with the weighing scale. Electronic ID displayed in the scale and ear tags were double-checked during weighing to ensure all tags matched automatic electronic records. The BWs, with corresponding heifer ID numbers and timestamps, were stored for further processing.

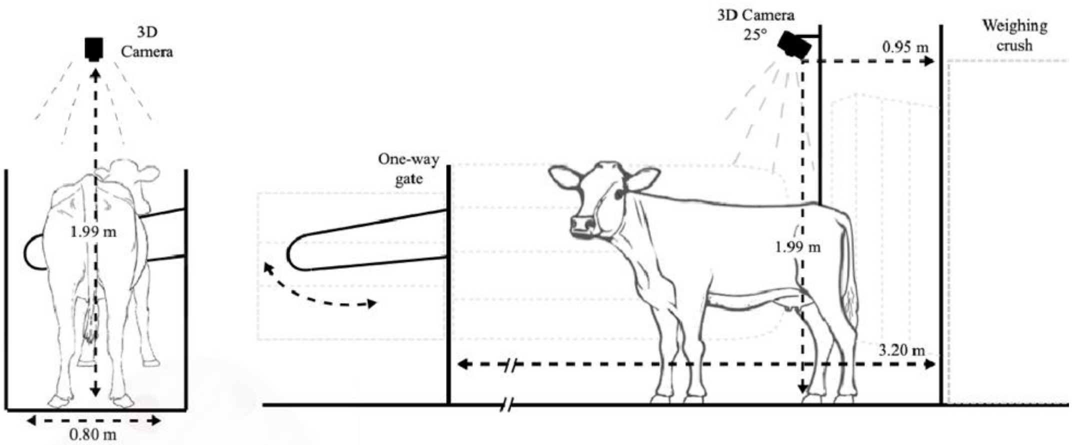
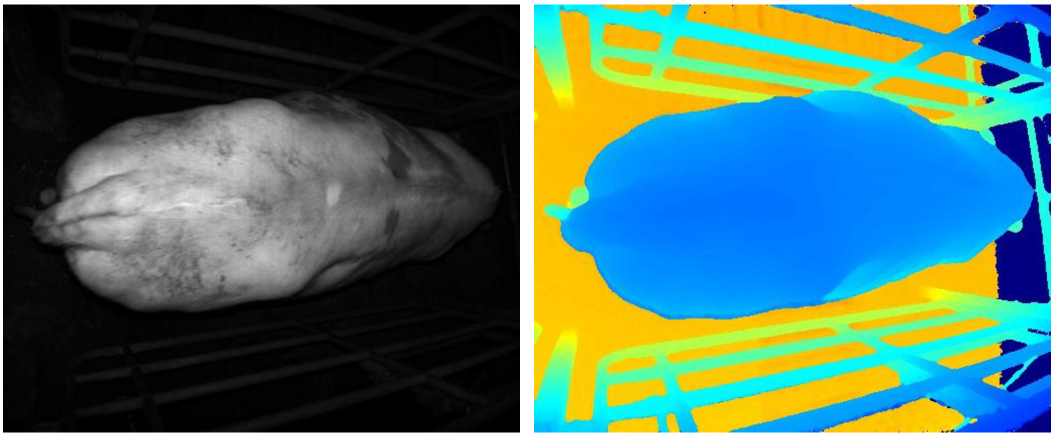


Figure 1. Illustration of data image collection setup.

Upon the heifers' return to their respective housing units and subsequent exit from the weighing scale, overhead rear-body view 3D images of each heifer were collected using a 3D TOF camera provided by DeLaval International AB, Tumba, Sweden (Figure 1 and Figure16, Appendix A). The camera was positioned 95 cm into the straight return alley, at a vertical distance of 199 cm from the floor to the camera's nadir, and angled at 25 degrees, to capture an overhead caudal rear view of each heifer separately (Figure 2). The camera was automatically triggered and activated upon identification of a movement within the frame view. The images, together with the corresponding time stamp, were transferred to a computer via an ethernet port for storage. For optimal image acquisition, the momentary pause upon the scale, necessary for the weighing process, ensured that each heifer was positioned individually beneath the camera for image recording. Additionally, a one-way gate (320 cm into the return alley) regulated the heifer's passage speed for optimal image acquisition. The weighing and image collecting procedure typically spanned over one hour, conducted within the timeframe of 8:00 am to 9:00 am.

Figure 2. Grayscale intensity image (left) and a depth image (i.e. point cloud) (right) of the caudal



rear view.

Data cleaning and identification matching

Manual cleaning of all BW recordings was conducted, resulting in the removal of approximately 30-40% of faulty recordings, with datasets of up to 130 recordings. The exclusions were attributed to various factors such as multiple recordings of a heifer remaining stationary on the scale for an extended duration beyond the intended timeframe, incomplete entries, or incorrect ID number associations with animal entries. The cleaned records of BWs, with corresponding heifer ID numbers and timestamps, were stored and kept undisclosed until the following day to prevent any potential bias.

Alongside the 3D images, 2D grayscale intensity images were stored on the computer. By matching the timestamps of image capturing and weighing the identification of each heifer was enabled.

3.3.2 Body Measurements

Three different BMs were collected for all heifers: Hipin using a foldable measuring stick (cm), external HJW a hipometer caliper (kg) (Dairy Innovations, Alexander, NY), and HH a sliding-scale height stick (cm) with a spirit leveler (Table 3; Figure15).

Table 3. Description of the three body measurements and the equipment to collect each body measurement

Body measurement	Description	Equipment

Hip Ischial width (Hipin)	External distance between the cranial edge of the hook bone and the caudal edge of the pin bone, measured unilaterally.	Measuring stick (cm)
External hip joint width (HJW)	External distance between the greater trochanters of the left and right femurs, measured posteriorly.	Hipometer (kg)
Hip height (HH)	Distance between the surface underneath the heifer hooves and the highest point between the hooks.	Height stick (cm)

Hipin was unilaterally measured on the left side as the external distance between the cranial edge of the hook bone and the caudal edge of the pin bone, determined by palpation and assessed with a foldable measuring stick (Figure 3; Figure A14Appendix A); HJW, was measured posteriorly with the hipometer caliper externally cupping the greater trochanters of the left and right femurs; and HH, was measured as the distance between the surface underneath the heifers' hooves and the highest point between the hooks, using the sliding-scale height stick adjusted to a level spirit (Figure 4; Figure A14Appendix A). The hipometer was used to estimate BW by measuring the width between the caliper arms cupping over the greater trochanters of the left and right femurs, corresponding to a sliding scale ranging from 32 kg to 750 kg. To decrease the risk of variation in pressure applied to the caliper arms during measurement, a calibration rod was used before each session. Beginning with the third data collection session, the height stick was also calibrated using the measuring stick to ensure the accuracy of the gradations between 105 cm to 190 cm.

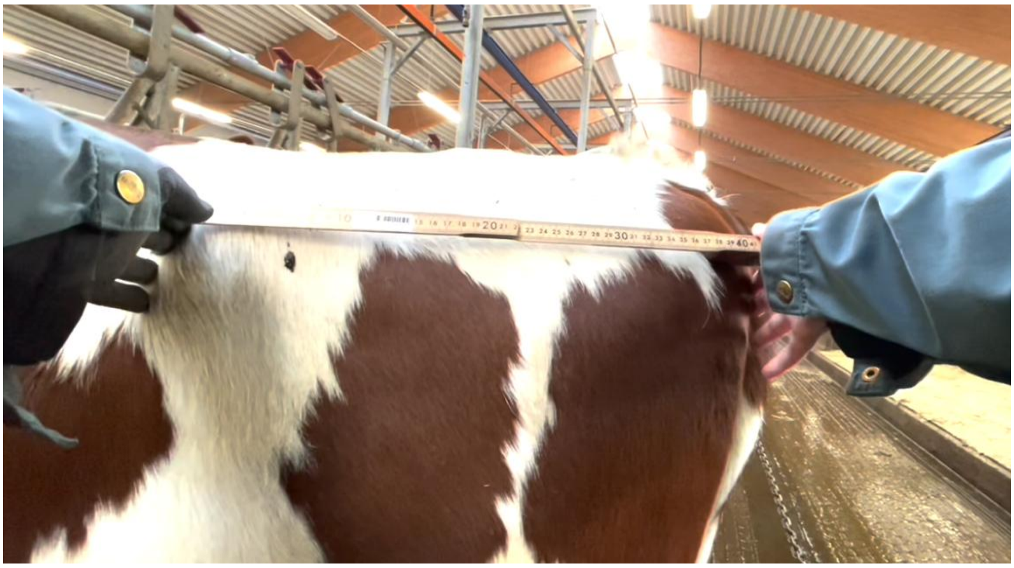


Figure 3. Picture of hip ischial width (Hipin) measuring with measuring stick (cm).

Figure 4. Picture of A) hip joint width (HJW) measuring with hipometer caliper (kg) (Dairy Innovations, Alexander, NY) and of B) hip height (HH) measuring with height stick spirit level (cm).

The body measuring was conducted following the heifers' return to their respective housing units. The measurements were performed sequentially by group, from unit one to four, as well as by body measurement, i.e. HH for all heifers in the group, thereafter Hipin etcetera. Upon entry into each unit, concentrate feed was administered and the heifers were trapped in the feed manger using the feeder headlocks to facilitate the collection of reference BMs. Once trapped, all heifers' front hooves were placed on a raised step, see Figure 4. A few heifers in each unit usually stayed in a laying position or refused to enter headlocks. This resulted in time spent driving up and herding heifers into headlocks, alternatively pursuing measurements in moving heifers. The heifers were released immediately after finalizing all BMs in their unit to minimize time fixated. It should be noted that the manual measurements caused stress for a smaller number of individuals, and several attempts to collect valid measurements had to be performed in those cases. A measurement was deemed valid when three repeated measurements yielded comparable results.

The measurements were conducted by the author throughout the study period, except for the first data collection. Typically, this part of the data collection took between 2 and 3 hours, consecutive after the weighing. Following each data collection, all measurements and corresponding heifer ID numbers were entered into Excel for further processing.

3.3.3 Body Condition Scoring

Body condition scoring was conducted for heifers in unit four, to specifically target those aged 12 months and above. The BCS was performed while the heifers were still fixated after the manual data collection of BMs. The scoring system used was a combination of the charts produced by Elanco Animal Health, Indiana, USA, and Geno SA, Hamar, Norway. In these scoring systems, the scoring is performed rear view, which resembles the camera angle utilized during the image capturing. Furthermore, the standardized scoring system was applied, ranging from 1 to 5 (with increments of 0.25), where 1 indicates emaciation and 5 indicates obesity. For the purpose of this study, specifically chosen anatomical areas, assumed to reflect body fat rather than growth development stage, were targeted for the BCS assessment of the heifers. Hence, the scoring included examination of the pins, tail, back and short ribs (Figure 5).

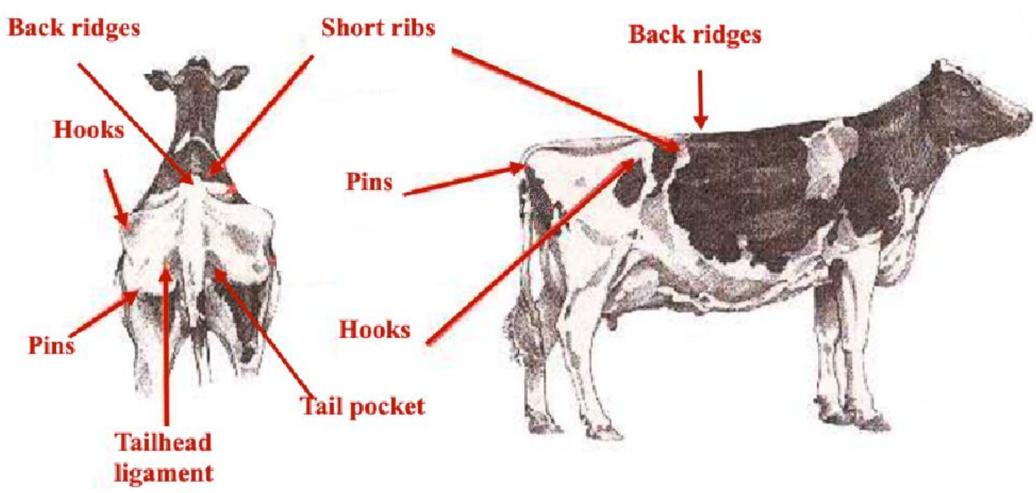


Figure 5. Illustration of the anatomical areas targeted for body condition scoring (BCS), adapted from Elanco Animal Health (1997).

The degree of fat padding on the pins was assessed by palpation (degree of softness) and visual observation of conformation. Rounded and softer pins gave greater scores compared to denser, triangularly conformed pins (Table 4). The tail area was palpatated and visually assessed, focusing on the depression around the tail and tail pocket, as well as the prominence of tailhead ligaments. A greater depression and prominence of the tailhead ligaments gave lower scores. The prominence of the back ridges and short ribs was visually assessed, with greater prominence resulting in lower scores.

Table 4. Description of visual assessment of the anatomical areas targeted for body condition scoring (BCS) in the study. The BCS charts produced by Elanco Animal Health, Indiana, USA, and Geno SA, Hamar, Norway were used as reference for the scoring assessment and determination.

Anatomical area	**Description**
Pins	Posterior view of the heifer. Determine if the pin bones are triangular (△) or rounded (O); the more rounded, the greater the score. Palpatate and observe the amount of fat padding over the pin bones.
Tail	Posterior view of the heifer. Palpatate and observe the depression/amount of fat padding around the tail, in the tail pocket and the prominence of the tailhead ligaments. The greater the depression and prominence of the tailhead ligament, the lesser the score.
Back and short ribs	Posterior and right lateral side view of the heifer. Observe the prominence of the back ridges and short ribs.

To ensure uniform assessments, each heifer was assessed from a posterior and right lateral side view in a relaxed standing position (i.e. not arching, urinating, defecating, or maintaining an elevated tail position). The scoring and body measurements were consistently conducted by the author of this thesis throughout the study period, except for the first collection session. Different assistants helped to record the values on the paper protocols. The recorded scores were entered into Excel with corresponding heifers ID numbers for further processing.

3.4 Statistical Analysis

The manually collected data was analyzed using complete observations by summary statistics, boxplots, and Pearson correlations to investigate the relationships between BW, manual BM (Hipin, HH, hipometer), BCS, age, and breed. Growth rates were analyzed by calculating the percentage difference in kg BW for each heifer between each data collection.

3.5 Image processing and model training

The image processing and model training were performed by engineers at DeLaval International AB, Tumba, Sweden. The author – and main BM scorer – performed manual annotations on randomly selected 2D grayscale images (n = 10) and dept images (n = 11) from the data collection, identifying anatomical landmarks replicating manual BMs of the heifers, i.e., hook bones, the hip height reference point i.e., center between the hook bones, and pin bones (Figure 6). The 22 annotated images were used by engineers at DeLaval as a reference to manually label all images with a web-based image annotation tool (COCO). Based on the labeling, measurements of the Hipin (distance between the annotated hook and pin) and HW (distance between the two annotated hooks), were extracted from the depth images and thereby synthetic BM estimations were created. The HH was calculated knowing the distance between the camera and the ground, thus, the distance from the 3D camera to the labeled HH reference point region was subtracted to estimate the HH.

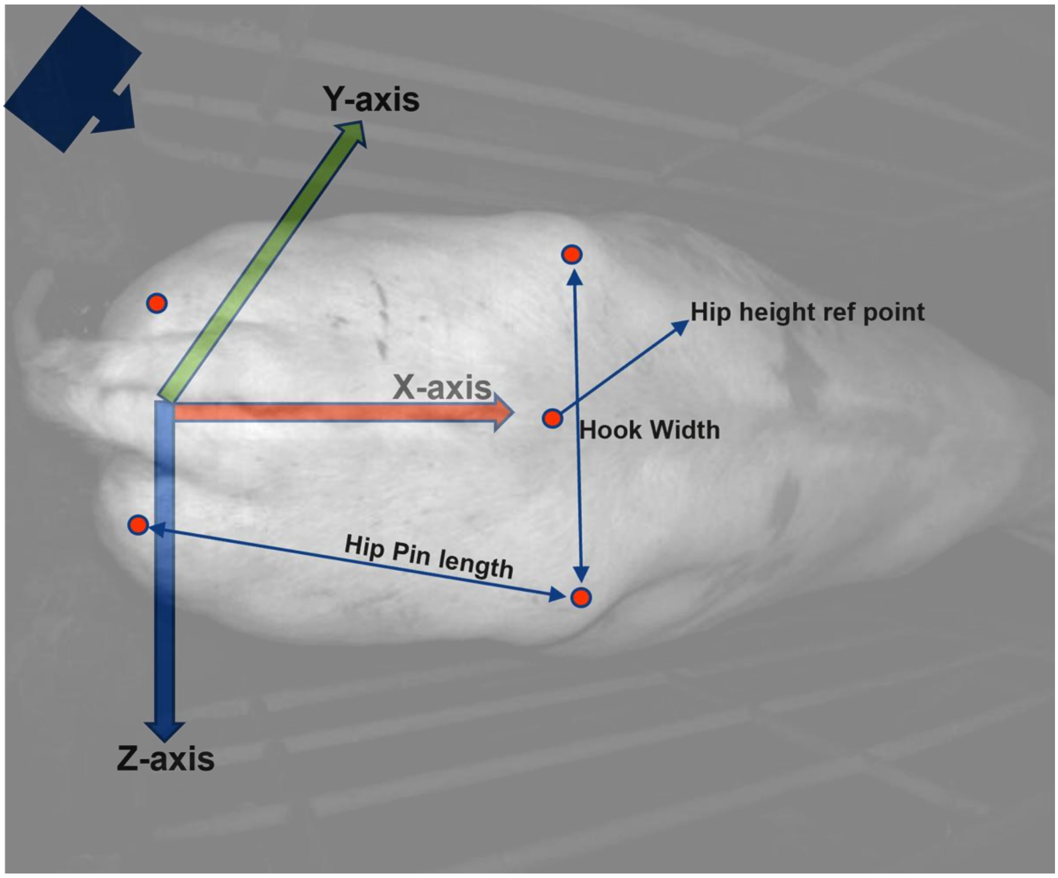


Figure 6. Depth image of caudal rear view with annotated anatomical landmarks for body measurements hip ischial width (Hipin), hip height (HH), and hip width (HW).

The collected reference data of BWs was cleaned using boxplots identifying outliers. A Gradient boosting regression model was used to predict BW, using the input variables extracted from the depth image BM estimations (i.e. Hipin, HH, and HW) together with age in months. The model was evaluated using cross-validation. To prevent leakage between test and validation, the cleaned data was divided into 80 % for test and 20 % for validation based on heifer ID. Thus, for model training 81 individual heifers (479 data points) were used, and the model was validated on the remaining 20 individual heifers (120 data points).

The output from the model was BW of the heifers in kg. As evaluation metrics, root mean square error (RMSE) (kg), R^2 score, and relative error (RE) were calculated.

4. Results

In total, 620 BWs and BMs were collected, distributed 350 SRB and 270 SH, involving 101 individual dairy heifers (59 SRB and 42 SH). The number of recording days per individual varied (Figure 8) and differed in frequency between age and breed (Figure 7). Four incomplete data points of BW (n = 3) or BM (n = 1) were identified and excluded from the statistical analysis. For animals aged 16 to 20 months, only 26 data points were available. Further details can be found in Table B1, Appendix B.

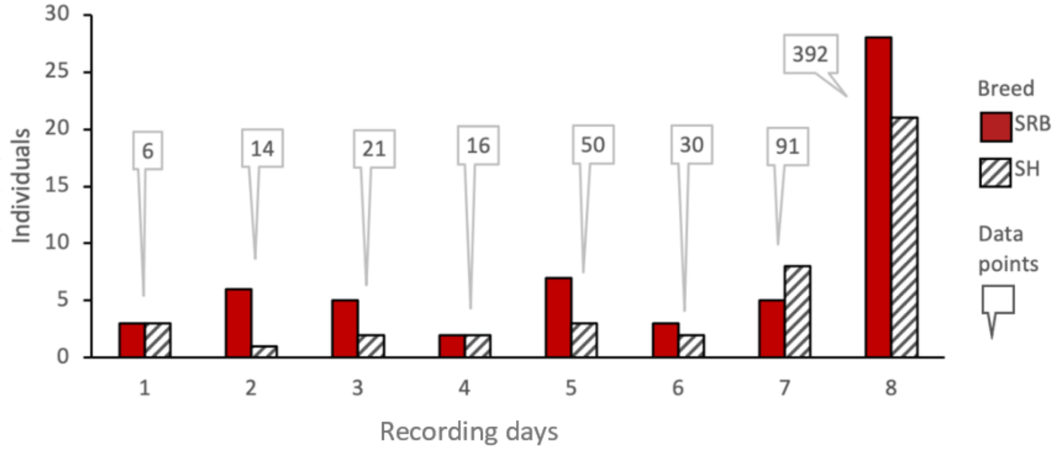


Figure 8. Number of recurring measurements per individual for Swedish Red (SRB) and Swedish Holstein (SH), as well as the total amount of data points.

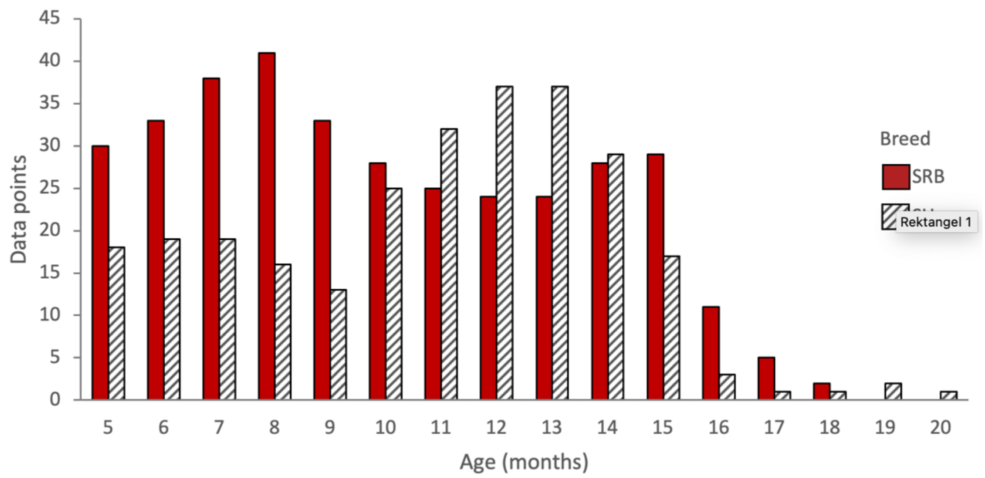


Figure 7. Number of data points per age for Swedish Red (SRB) and Swedish Holstein (SH).

4.1 Body weight and manual body measurements

All manual BMs as well as BWs showed, as expected, a positive relationship with age (Figure 9). The mean BW was 391.2 kg, ranging between 196.0 kg and 616.0 kg. The SH heifers had an overall higher mean BW compared to SRB from 7 months onward (Figure 9A). For both breeds, the relationship between BW and age was as expected positive and followed a steady increase until 16 months for SH and 14 months for SRB, where momentary drops could be observed, followed by a resume to a steadily increasing trend. An increasing spread of mean BW could be observed from 11 months in both breeds. There were slight overlaps of mean BW between breeds at all ages, with higher occurrence at 11 and 13 months.

The mean BW value estimated by the hipometer was 391.4 (min: 206.0; max: 606.0) kg, indicating a similar mean value and larger spread compared to true BW values. The spread of BW estimates by the hipometer was clearly larger in older animals (Figure 9B).

The mean value for Hipin was 46.24 (min: 35.00; max: 55.00) cm, HH 132.2 (min: 110.0, max: 150.0) cm. For SRB, there seems to be a tendency for a shorter Hipin, as well as a larger spread compared to SH (Figure 9C). The HH was clearly lower for the SRB compared to SH at all ages (Figure 9D). In Table 5 all mean values and spread per breed are found. Further descriptive statistics for all variables can be found in Table B2. Appendix B.

Table 5. Mean values and spread per body measurement and breed.

Body measurement	**Swedish Red (SRB)**			**Swedish Holstein (SH)**		
	Mean	*Min*	*Max*	*Mean*	*Min*	*Max*
Scale weighted BW, kg	372.3	198.0	616.0	415.6	196.0	601.0
Hipometer, kg	369.3	206.0	606.0	420.7	213.0	606.0
Hip ischial width (Hipin), cm	45.16	35.00	55.00	47.66	37.00	55.00
Hip height (HH), cm	128.0	110.0	148.0	137.8	117.0	150.0

The BMs were conducted by the author on seven out of eight occasions, with the first conducted by another assessor. Some inter-assessor variability was observed using scatter plots (data not shown) in the hipometer measurements, as the first collection recorded generally lower weights compared to the author's subsequent measurements.

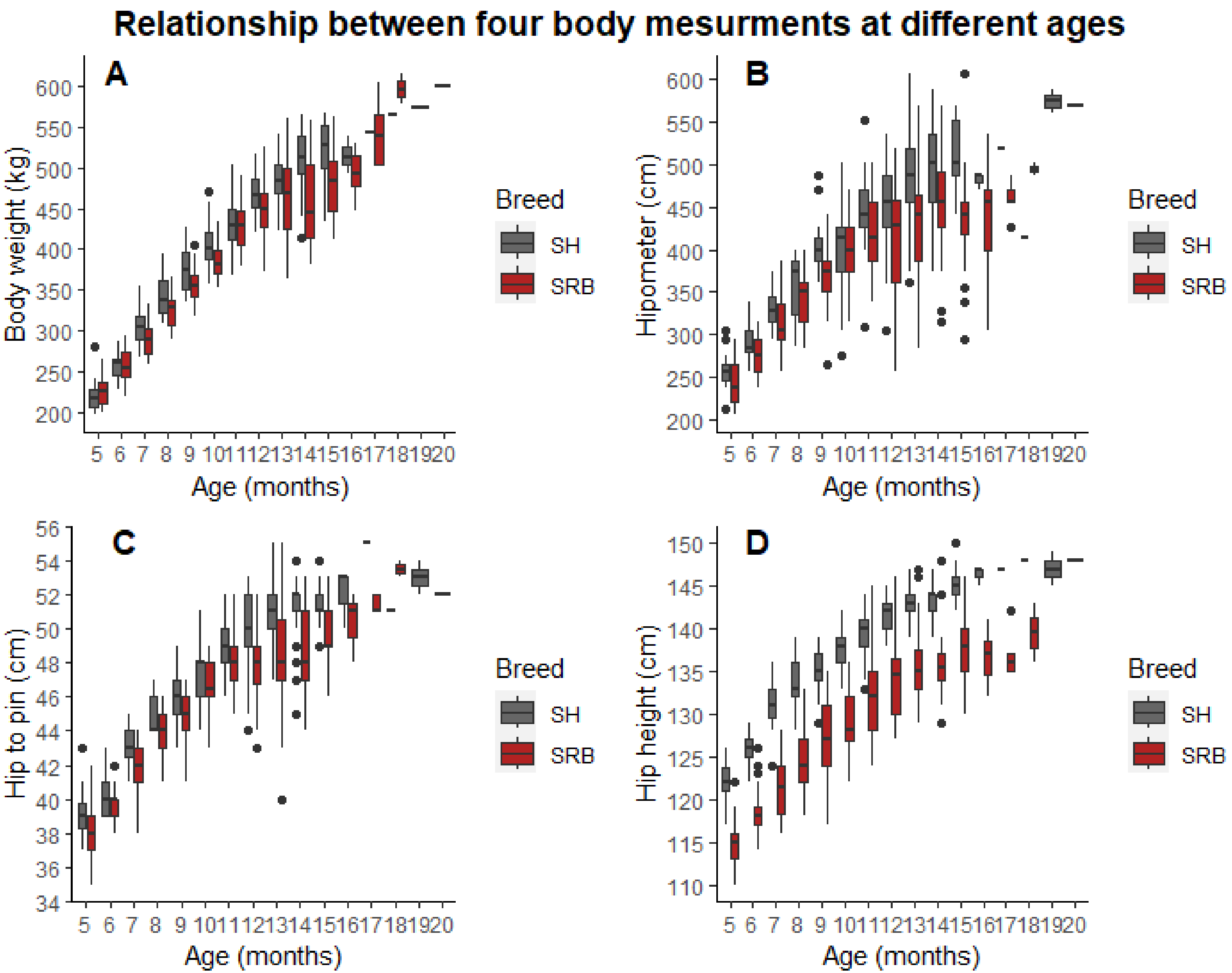


Figure 9. Boxplots illustrating the relationship between age and A) true body weight (BW), B) hipometer, C) hip ischial width (Hipin), and D) hip height (HH) for Swedish Red (SRB) and Swedish Holstein (SH).

4.2 Growth and body condition score

The growth rate was mainly positive for both breeds, with a mean growth rate of 4 % (approximately 15 kg) between measuring occasions (Figure 10). On average, for both breeds, the highest growth rates occurred at 5 to 6 months, and lowered with increasing age thereafter, with a slight temporary increase at 12 and 15 months. The SRB heifers exhibited the highest and lowest data points of growth rate (the same individual) with an approximate 11.5 % (33 kg) increase at 7 months and a - 3.50 % (-11 kg) decrease at 8 months.

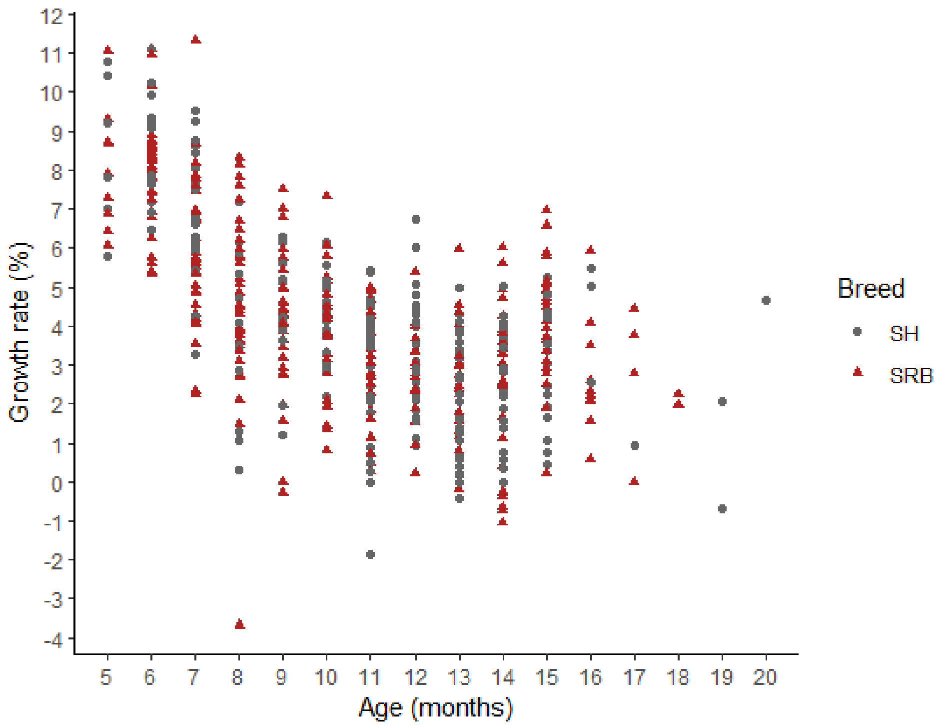


Figure 10. Growth rate (%) distributed by age for Swedish Red (SRB) and Swedish Holstein (SH).

The mean BCS among the selected heifers (≥ 13 months) was 3.5 (min: 3.0, max: 4.0). There was a high variation in BW distribution per BCS. A positive trend was observed, meaning heifers with higher BW in general received higher BCS (Table 6). For SRB, only one data point was recorded for BCS 3.0 and was identified to deviate from the individual heifer's successive BCS recordings, indicating an erroneous assessment.

Table 6. Body weight (BW) distribution based on body condition score (BCS) for Swedish Red (SRB) and Swedish Holstein (SH).

Breed	BCS	Body weight		
		Mean	*Min*	*Max*
SRB	**3.0**	544	544	544
	3.25	474	393	616
	3.5	473	400	565
	3.75	511	414	604
	4.0	515	509	525
SH	**3.0**	424	415	433
	3.25	507	446	563
	3.5	513	422	601
	3.75	517	465	577
	4.0	563	552	573

4.2.1 Correlations

Body weight showed to be overall strongly correlated with all manual BMs (r = 0.88 - 0.94), as well as age (r = 0.93) but weakly correlated with BCS (r = 27). Discerning breeds, slightly stronger correlations were found for SH between BW and hipometer, BCS, and age (Table 7). All correlations were significant.

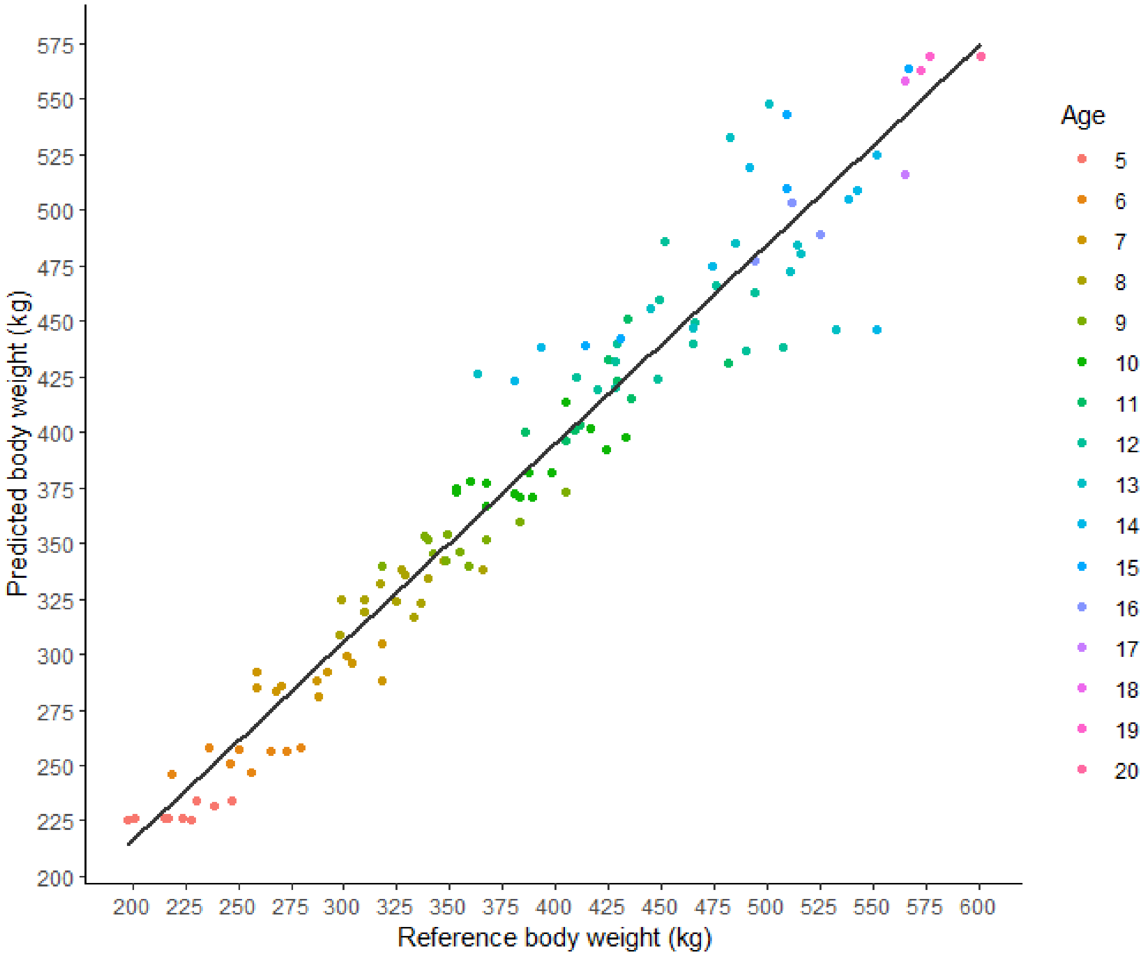
Table 7. Pearson correlations between body weight (BW) and manual body measurements (BM), body condition score (BCS), and age.

Body measurement	n			Pearson Corr (r)		
		SRB	*SH*		*SRB*	*SH*
Hip ischial width (Hipin), cm	101	59	42	0.94	0.94	0.94
Age, months	101	59	42	0.93	0.93	0.94
Hip height (HH), cm	101	59	42	0.88	0.92	0.92
Hipometer, kg	101	59	42	0.88	0.86	0.90
BCS	43	23	20	0.27	0.22	0.30

4.3 Image processing and model performance

The RMSE for the estimated BW was 26.0 kg (± 2.5 kg), with a RE of 5.35 % (± 0.51 %), and R^2 score of 0.93 (± 0.02). Regarding deviations from actual BW, 37.5 % of the heifers had an estimated error of less than 10 kg, while 36.0 % deviated by more than 20 kg. The largest individual error was observed in a SH heifer, where the model underestimated the BW by 50 to 106 kg, with the deivation increasing with each successive measurement.

Figure 11 illustrates a regression plot of reference BW vs predicted BW from the best-performing fold from the cross-validation. The Gradient Boosting model



slightly underestimates BW, with the largest error for age groups between 12 to 15 months. Overlapping also occurred within the age span of 12 to 15 months.

Figure 11. Regression plot of reference vs predicted body weight (BW) based on input features from computer vision (CV) body measurements (BM) hip ischial width (Hipin), hip height (HH), hip width (HW) and age in months, illustrated by age groups

The BM estimations extracted from depth images of HH and Hipin were consistently lower than the manual measurements, as depicted in Figure 13A-B, indicating an underestimation by the model. The RMSE for estimated HH was 6.6 cm and for Hipin 5.9 cm. Slight differences in estimations between breeds were observed.

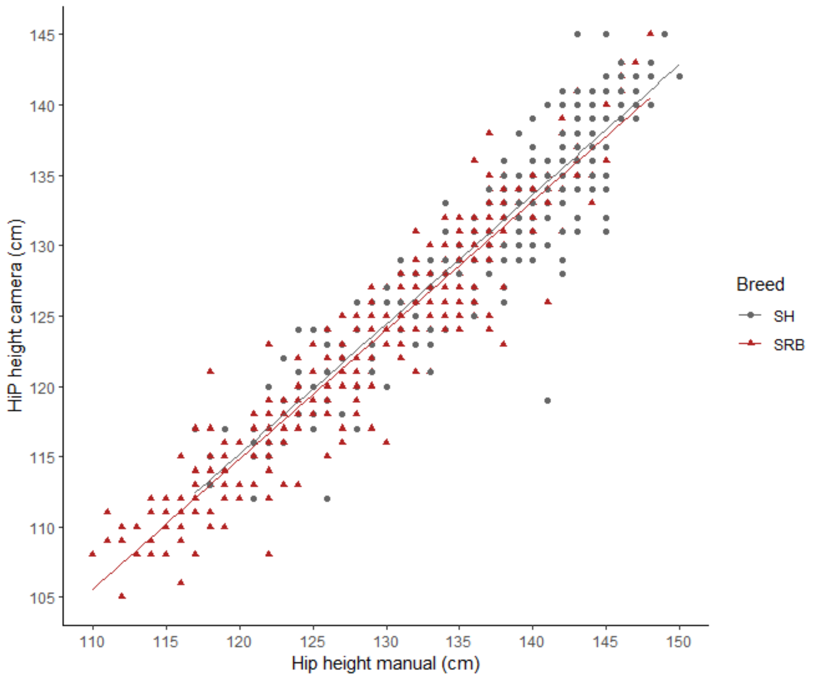


Figure 12A. Scatterplot illustrating the relationship between the estimated and manual measurement of hip height (HH) showing breed differences.

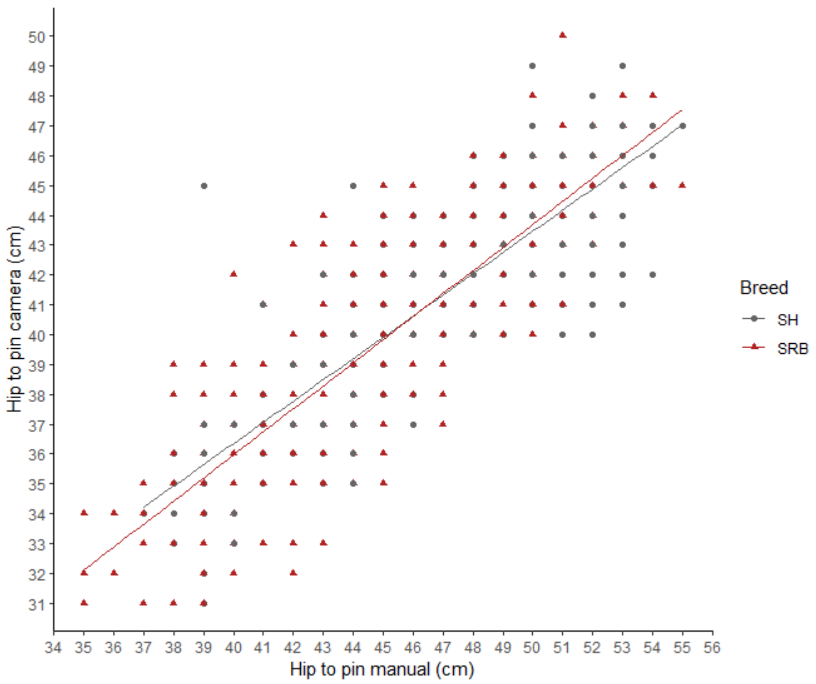


Figure 13Scatterplot illustrating the relationship between the estimated and manual measurement of hip ischial width (Hipin) showing breed differences.

5. Discussion

The present thesis evaluated the use of 3D CV technology to estimate the BW of growing dairy heifers aged 5 to 20 months by improving the angle of imaging. The results showed strong correlations between heifer BW and all reference BMs. By extracting these strongly correlated BMs from depth images and utilizing them as input features to a BW estimation model, sufficient predictive accuracy for heifer BW was achieved (RMSE 26 kg). These findings support that 3D CV technology with an overhead rearview imaging could enable automated and timely youngstock monitoring and management by enabling optimal BM extractions.

Previous research has shown the promise of this approach for both adult (Tasdemir & Ozkan 2019; Martins et al. 2020) and young cattle (Song et al. 2014; Le Cozler et al. 2022; Ahlberg 2024). Ahlberg (2024) encountered challenges related to camera angle which led to difficulties in identifying anatomical landmarks, resulting in poor performance of their 3D CV model (R^2 = 0.53). However, when the manually collected BMs, which correlated strongly with heifer BW (Hipin, HH, hipometer, HW, wither height, backside width, and chest girth) identified by Ahlberg (2024), were integrated as input features in their model, performance was notably enhanced to R^2 = 0.81. The approach of this study improved the data collection and increased the correlations between BMs – Hipin, HH, and hipometer – and BW. Extracted from depth images and used as input features, the BMs (with HW as a appproximaton for hipometer) increased the performance of our model further (R^2 = 0.93), underlining the critical importance of optimal input selection to achieve optimal output in such models (Wang et al. 2023).

5.1 Refinement of model

5.1.1 Manual measurements

The investigated BMs within this study – Hipin, HH, and hipometer – are shown to strongly correlate with cattle BW, as found in previous research (Heinrichs et al. 1992; Dingwell et al. 2006; Song et al. 2014; Ahlberg 2024). However, reservations for the hipometer's accuracy at greater ages and BWs were noted both in this study and in previous research (Dingwell et al. 2006). These measurements were also easily obtained in headlock-fixated animals as they focused on the hindquarters. The heart girth measurement, a commonly used tool for BW assessment in growing heifers, which has also previously shown a strong correlation to BW (Heinrichs et al. 1992; Dingwell et al. 2006), was excluded as it requires close, prolonged animal contact at the front legs, increasing stress for the animal and injury risk for the assessor (Heinrichs et al. 1992; Dingwell et al. 2006; Ahlberg 2024). Moreover, in order to automatically record images of the heifers, it is beneficial to capture a reduced anatomical area, making heart girth measurement impractical.

As stated by Wang et al. (2023), Enevoldsen & Kristensen (1997), and reflected by this thesis results, accuracy in measurements benefits from prominent anatomical landmarks. The Hipin measurement relied on the prominence of the hook and pin bones on one lateral side, which were easily identified through a combination of visual estimation and palpation, resulting in a stronger correlation. The HH measurement, taken at the visually estimated highest point between the hooks, might decrease in accuracy and correlation due to visual estimation variability. The hipometer, as a calibrated tool relying on external HJW (Dingwell et al. 2006), faced challenges in larger heifers due to the caliper arms not fitting over the hindquarters to reach the hip joints, and difficulty in identifying less protruding hip joints, leading to weaker correlations. Furthermore, the hipometer's sensitivity to correct application of pressure can lead to variations, both intra- and inter-assesssor.

Notably, some heifers in the study were observed to have narrower HJW than the norm, which would lead to misleading BW estimations. Figure 9D shows increased variation in hipometer measurements from 10 months of age (approx. 400 kg SH; 380 kg SRB), indicating increased difficulty in performing measurements and correlating with observed measurement difficulties. This aligns with Dingwell et al. (2006), where the hipometer performed poorly outside of the age span 3 to 15 months, correlating to approximately 200 to 400 kg. The results of this thesis also suggests earlier difficulty in estimating BW for SRB by hipometer, as the SRB had lower BW at 10 months than SH, further supported by the slightly stronger correlation between BW and hipometer for SH (r = 0.90 vs 0.86).

The scale-weighed heifer BWs served as reference values for the assessment of the predicted BWs obtained from the Gradient boosting regression model. To enhance the reliability of these BW reference values and mitigate potential errors, such as faulty scale recordings, successive measurements were conducted for all individual heifers throughout the study period. This approach facilitated the identification of outliers for individual heifers, allowing for correction from the raw dataset or exclusion of erroneous measurements.

Additionally, the correlation between BW and age in months was found to be the second strongest among all variables in the study, indicating the significance of age in BW estimation. This correlation aligns with previous research by Ahlberg

(2024). Thereby, age was included alongside BMs to enhance the performance of the 3D CV model.

5.1.2 Automatic measurements

The camera setup in this study, positioned in a straight walkway with controlled throughput of the heifers i.e., the time delay between successive heifers and a one-way exit gate, aimed to optimize image capturing for extraction of BMs and estimation of BW. This approach minimized noise sources identified in earlier research, such as high-velocity movements (Salau et al. 2015), non-optimal camera angles, and distances between the camera and cattle (Vázquez-Arellano et al. 2016; Ruchay et al. 2020; Kamchen et al. 2021; Wang et al. 2023; Ahlberg 2024).

The dorsally focused anatomical area allowed for a lower, closer, and angled camera mounting, improving BM extraction by providing clearer imaging of hooks and pins. Consequently, these were some of the modifications that most likely contributed to enhanced BW estimation compared to the setup by Ahlberg (2024) using full-body top-view imaging (R^2 = 0.93 vs 0.53, respectively). Other potential noise sources like light reflectivity differences (due to fur color and texture) (Salau et al. 2015; Vázquez-Arellano et al. 2016) and adverse conditions such as dust and light (Vázquez-Arellano et al. 2016; Ruchay et al. 2020) was not encountered in the present study's indoor environment and short duration. However, dust accumulation can be expected in indoor housing over a longer period of time than the one used in the present study and direct sunlight can also be expected to cause noise (Vázquez-Arellano et al. 2016). Future mountings for 3D imaging should consider these concerns and accessibility for maintenance (Martins et al. 2020).

Utilization of multiple camera viewpoints, such as addition of a sideview, could contribute to the BM extraction by increasing the information in the depth image. However, in this study, the utilized camera angle proved sufficient for capturing the necessary heifer's body curvature and contours for accurate BW extraction, as illustrated in Figure 6. Implementing sideview cameras present practical challenges, including difficulties in mounting without disrupting the housing enviorment, as well as the risk of interference by heifers and exposure to dirt, dust or feaces, which could affect image quality. Additionally, these factors would increase costs, making the use of multiple cameras less feasible in this context. For this reason,….using a single overhead rearview camera appears to be the most practical, acurate and cost effective way to estmate body weight in heifers.

5.2 Future refinement

Continued efforts to enhance the accuracy of all BM extractions, potentially surpassing reference BMs obtained with standard manual methods, stand to further improve the performance of the 3D imagining techniques.

Heifers in the age groups between 12 to 15 months showed the largest spread i.e., the highest occurrences of both under- and overestimations in BW predictions (

Figure 11). The skeletal growth reduction, often occurring at 12 months (Hammack & Gill 2009; Craig et al. 2016), may have influenced the accuracy in BW estimations of heifers in the age groups. Additionally, a trend shift from under- to overestimating BW with increasing age may correlate with greater difficulties in extracting BMs from younger heifers with less developed skeletal frames. Lobo et al. (2019) highlight the importance of considering differences in calf development when extracting BMs from anatomical landmarks, especially in automated systems. For example, when comparing the Hipin and HH estimated from the depth images to the manually measured (Figure 13A-B), both features were underestimated by the Gradient boosting regression model. When fixated in the feed manger, the front hoofs of the heifers were elevated upon a raised level (Figure 4B), which may change their stance in such a way that the reference BMs were slightly affected (i.e., heifers reference HH slightly overestimated). In future research with similar housing setups, avoidance or adaptions to such conditions should be made to ensure consistent manual collection of reference BMs. Additionally, consistent estimating of Hipin across heifers can be challenging due to the downward curvature of the pin. A model capable of reading the curvature could improve the accuracy. Further factors identified within the study to potentially contribute to difficulties in identifying anatomical landmarks – such as hooks and pins – from depth images include excessive BCS and seasonal variations in coat lengths and thickness.

It is important to note that the reference values reliability, while improved by repeatability as has been discussed, is susceptible to influence factors. Despite almost exclusively being performed by one assessor, the subjectivity of humans will have an effect (Wilkins et al. 2015). As will the previously mentioned stance variations in cattle (Gaudioso et al. 2014), particularly in nervous animals. Additionally, calibrated scales can be adversely affected by placement on curved surfaces (Lobo et al. 2019). Even though the scale in the present study was placed on a flat surface, it is still possible other unknown issues may result in erroneous data. This was illustrated by the growth rates calculated from the scale weighed BWs, where the highest and lowest data points recorded were for the same individual within the same month (Figure 10). Negative growth rates found in the present thesis could therefore be a result of faulty scale measures, but more likely reflect a true body weight loss or lack of growth.

Compared to traditional scales, the 3D TOF camera system suggested in this thesis offers the possibility to estimate numerous measurements daily, providing a more comprehensive picture of weight changes over time and reducing the impact of any single erroneous measurement. Furthermore, heifer BW fluctuations within-day and day-to-day can be better captured, and might be reflected within the RMSE of 26 kg in this study. Considering the trade-offs in terms of more reliable trend analysis, time efficiency, reduced labor, and minimized stress and injury risk for both the heifers and the handlers, the RMSE is considered sufficient.

Due to time constraints in the study, the HW measurement from the depth images was used as a rough approximation of the hipometer, thus incorporated as one of the input features to the Gradient boosting regression model. Since the hipometer has shown to have higher correlation to BW (r = 0.88 and r = 0.91 in Ahlberg (2024)) compared to HW (r = 72 in Ahlberg (2024)). This suggests that substituting HW with external HJW could potentially enhance the performance of future BW estimation models. Moreover, extracting the external HJW measurement through 3D CV holds promise for refining the hipometer measurements. Firstly, this method could eliminate the influence of assessor consistency in applying appropriate pressure on the caliper arms (Dingwell et al. 2006). Secondly, it addresses the limitation of the caliper arms not being wide enough to fit over the hindquarters to reach the hip joints. This means that restrictions observed in hipometer-estimated BWs within this study and other research (Dingwell et al. 2006; Ahlberg 2024), particularly concerning heifers of greater age and BW, could be partly circumvented.

Implementation of the hipometer in future reaserch as a reference value could still hold value. While it is effective, it’s sensitivity and limitiations reduce it’s overall usefulness. Incorporating a pressure indicator would help ensure consistent pressure application during measurements, thereby enhancing the robustness of the method.

The BCS showed a tendency of an increase in BW and BCS but showed only a weak correlation to BW (r = 0.27), suggesting limited enhancement potential for the BW prediction model and hence was excluded. This may be partly due to the use of charts designed for fully matured dairy cattle (as no BCS charts for growing dairy cattle are available) as well as the assessor’s relatively low experience in BCS assessments and the influence of different recording assistants. As the skeletal development of heifers might not have been fully matured at assessments within this study, given that heifers are reported not to have achieved full stature at 12 months (Craig et al. 2016), it is crucial to recognize heifer-specific growth characteristics during assessment (Elanco Animal Health 2004). Therefore, future assessments would benefit from using charts specifically designed for dairy heifers (or possibly, charts tailored for growing beef heifers or specific breeds). These highlight the risk of human error while using subjective scales to measure BCS. Therefore, there, using objective measures of images using automatic equipment could overcome the subjective human factor and improve reliability in BCS assessments. . Including BCS in 3D CV estimations for BW, as suggested by Enevoldsen & Kristensen (1997), should further improve the model's BW estimation accuracy by contributing information of body conformation.

Despite the robust data set collected throughout the study, few data points were recorded in the oldest age groups (≥ 16 months). Conclusions drawn for these age groups should therefore be approached with caution and validated through further research. Additionally, the model's applicability is limited to the two breeds (SRB and SH) and the farm of the current study. With further model training of larger data sets, additional breeds, and multiple farms, the model's performance and applicability should be enhanced. Differences in automated BW estimations for breeds are believed to emerge (Wang et al. 2023) and incorporating breed as an input feature in future models could further enhance their performance. Incorprating herd-specific information is further belived to enhance the models performance on a herd level (Wang et al. 2023).

5.3 Breed & body composition

In this study, the two breeds included showed different growth trajectories as evidenced by both manual and 3D CV estimated BMs. While these differences were to be expected, the results of this thesis shed further light on the dynamic nature of heifer development which is crucial for timely management adaptations tailored for the different breeds (Wang et al. 2023).

The well-known observation that SH generally has greater stature compared to SRB (Kalvportalen 2019) was established, as evidenced by higher mean BW, Hipin, HH, and hipometer measurements for any given age (Figure 9A-D; Table B2. Appendix B).). Correspondingly, the BCS values of SH aligned with higher mean BWs than those for SRB (Table 6). The BW accumulation followed a steady increase in both breeds until around 12 months of age, after which a decline was noticeable (Figure 9A). This decline coincides with the anticipated reduction in skeletal growth concurring with pubertal onset (Hammack & Gill 2009; Craig et al. 2016). This decline is further supported by a decrease in the increase rate of Hipin and HH observed at 12 and 13 months respectively (Figure 9C-D), indicating a reduction in skeletal growth. The increasing overlap of BW between breeds at 11 and 13 months may be attributed to differences in the timing of the decline in skeletal growth between and within breeds. The decline in BW accumulation is also evident by the decrease in growth rate until 11 months, with reduction observed as early as 7 months of age (Figure 10), which reflect earlier reporting's on growth curve dynamics by Handcock et al. (2019a). The growth rate dynamics within this thesis may be further affected by changes in diet, particularly by the relocation out of the first unit, at approx. 7 months, where concentrate feed was offered. Before 7 months, the BW distribution between the breeds was more similar, while Hipin and HH measurements of SH remained greater than that of SRB, indicating a greater accumulation of non-skeletal tissues in SRB. This could be attributed to the greater inclination of SRB towards increased fat accumulation (Kalvportalen 2019). Notably, research suggests that nutritional manipulation is of significant importance in younger animals than those included in this study for future performance (Gasser et al. 2006a; Cardoso et al. 2014). Investigating the application of the BW estimation model on younger heifers could thereby be beneficial for further enhancement of lifetime performance. For instance, BW estimation of calves, from 6 days of age, has been obtained through mounting cameras on automatic calf feeders (Song et al. 2014). Furthermore, assessing BCS in younger heifers than those in this study could enhance the understanding of the nutritional impact.

5.4 Functional adoption to farm management systems

The placement of the camera within youngstock housing can pose a challenge. Application for milking dairy cattle has utilized the frequent passage through milking machines by placement of BW systems in direct proximity, but in youngstock housing other incentives must be applied to uphold voluntary passage (Segerkvist et al. 2020). Sources of feed, lying area (Nir et al. 2018), water, salt, and minerals have in similar studies with youngstock been found to be attractive incentives for passage through BW estimation systems when offered in restricted locations (Segerkvist et al. 2020). The attractiveness of the incentives is intricate to the frequency of BW recordings, and therefore the possibility of timely adaptations to management. Furthermore, the design of the passage also plays a crucial role in the frequency of passage and the usable image acquisition (Segerkvist et al. 2020; Wang et al. 2023). The compact size of the camera (He & Chen 2019) offers an alternative with little to no visible disruption or alteration to existing housing. A usual approach is mounting upon an existing frame at a passage (Song et al. 2014; Hansen et al. 2018), which is beneficial to both lessen the disturbance to cattle and the environmental and economic impact of material use.

With automatically triggered 3D image collection to estimate BW follows the need for accurate automatic recording of the corresponding heifer ID. Within this study, a type of radio frequency identification (RFID) ear tag was used, which is a common identification method within cattle operations (Ruiz-Garcia & Lunadei 2011). This technology offers the implementation of reader triggering for image capturing and the implementation of software-controlled gates that controls the cattle traffic for individual animal recordings (Wang et al. 2023). However, as demonstrated in this study, they pose a risk for faulty recordings and can according to Awad (2016) pose reliability issues in large herds with challenging environments. An interesting alternative is the use of biometrics with deep learning techniques, which identifies unique individuals by physiological characteristics such as muzzle, retinal, iris, facial, and coat patterns. The development of these approaches is ongoing and shows promising progress in identification accuracy (Qiao et al. 2021). For example, Zin et al. (2018) showed an identification accuracy of 97.01 % based on back images. This approach could be interesting to integrate into future development of 3D CV models like this, and the non-invasive nature could promote animal welfare.

5.5 Future possibilities

Within the identified need for efficient and effective technical support in youngstock rearing (Palczynski et al. 2022; Doidge et al. 2024), farmers have highlighted the need for these systems to integrate data, reduce time spent on performance recordings, simplify information into specific outputs, and enhance accessibility to historical performance data to facilitate decision-making, without disturbance to the animals. Measures towards these goals are already ongoing in PLF technology, aiming to improve dataset utilization and simplify dataset acquisition by integrating systems that utilize shared traits (Wang et al. 2023). Examples of research within this area are simultaneous monitoring of BW, BCS, and mobility, as performed by Hansen et al. (2018) and by Martins et al. (2020). The current study's work towards extracting accurate BM from 3D depth images could similarly contribute to BCS and skeletal development monitoring, supporting the PLF technology that is yet to be commercially available.

As stated by Enevoldsen and Kristensen (1997), BMs can be utilized to device tailored growth curves, which, combined with automated BW estimations and implicitly given growth rates, can contribute to the early detection of unfavourable deviations in growth. As advancements in PLF technology emerge for youngstock – such as the automated BW estimations suggested in this thesis, skeletal development monitoring, BCS, or heat detection – a deeper understanding of the dynamics between these metrics and their implication on performance variables can be identified. Lifetime monitoring allows for conclusions on the best heifer management practices to optimize lifetime performances, filling a common knowledge gap in today's dairy operations (Palczynski et al. 2022).

Considering the time-consuming nature demonstrated by the reference value collection in this study, the need for such technology is strongly emphasized. Additionally, the robust dataset offered through such technology increases the validity of the data on which farmers base their management decisions and circumvents the fragility of sparse measurements.

6. Conclusions

Our results confirm that the BW of developing heifers can be accurately estimated through the application of 3D CV technology. Specifically, our findings demonstrate that images captured from an overhead rearview angle provide information that surpasses previous efforts utlizing alternative camera angles. This advancement enabled the extraction of necessary body measurements for development of an BW estimation model that demonstrates strong predictive accuracy for individual heifers. The study confirmed strong correlations between the investigated BMs, Hipin, HH, hipometer as well as age with BW. Furthermore, the correct placement of the camera was shown to be crucial for an accurate extraction of these BMs from depth images.

We conclude that the technology presented in this thesis could directly benefit farmers by providing a cost-effective, minimally time-consuming, and labor-efficient tool. This non-invasive technology can be implemented on most commercial dairy farms to monitor the growth of dairy heifers, thereby improving nutritional management and optimizing health, reproductive, and productive lifetime performance. Furthermore, it can enhance the understanding of growth dynamics and important factors affecting lifetime performance, aiding in the identification of best practices and creating clearer incentives for their implementation.

6.1.1 Future work

Further improvement in the BW estimation model could be achieved through continued refinement of BM extractions from depth images, by evaluating the performance of other ML methods for the task. Within this study, one heifer was consistently and significantly underestimated by the model. This islotated case indicates that while the model shows potential, further work is required to address such anomalies. Furthermore, implementation of external HJW (hipometer measurements) could be of added value as well as implementing automatic annotations to identify anatomical landmarks in the depth images, which would standardize the input data. A method to automatically ID heifers is needed to streamline this process. Additionally, utilizing the technology to further understand the relationship between skeletal development and BW of breeds could improve estimations. Automation allows for continuous incorporation of herd-specific input, enhancing the model’s performance at herd level. Functional adoption to farm management systems should also be investigated, with consideration to implementation possibilities for animals younger than those in this thesis. Furthermore, the potential benefits and applications of the developed technology for further understanding optimal growth curves for enhanced lifetime performance should be investigated.

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Popular scientific summary

Young dairy cattle, also known as dairy replacement heifers or youngstock, are crucial for the future of dairy farms as they will become the next generation of milking cows. These cows produce the milk that generates farm income. Despite their importance, the costs and management of raising youngstock – and how this affects their future reproduction and milk production – are often given less attention and investment compared to milking cows. Youngstock's sparse monitoring, and thereby lack of information for farmers to make informed decisions from, is a significant reason for this. The sparse monitoring is a result of conventional methods like weighing scales or body measurements being labor-intensive, time-consuming, and costly, with risk of stress or injury to the animals and assessors.

To address this issue, this thesis aimed to validate the use of three-dimensional computer vision (3D CV) technology to estimate the body weight of youngstock. Body weight is a vital metric for farmers, acting as one of the few measurable ways to monitor and provide insights into growth, body condition, and overall health of the animal in response to management decisions. Thereby, regular monitoring of body weight helps farmers ensure their heifers are developing properly, which is essential for their future reproductive performance and milk production. This is especially important as it allows the animals to generate income, repaying the investments made during rearing and ensuring farm profitability.

To facilitate the 3D CV estimation of heifer body weights, 3D images were collected, whereof body measurements were extracted and utilized to estimate body weights in combination with age in moths for the individual heifer. To ensure the accuracy of the estimations, manual collection of scale weights and three body measurements were performed to compare estimations to. Furthermore, the collection of body measurements facilitated the understanding of which measurement had the strongest correlation to body weight and thereby aided the most in estimations.

The results validated that 3D CV technology can estimate the body weight of youngstock with sufficient accuracy, outperforming previous methods. Key measurements identified with strong correlations to body weight included age in moths, hip ischial width (length between hook and pin), hip height (height of hip from floor), and hipometer (external hip joint width). Optimal camera placement was crucial for accurately extracting measurements. The study also identified ways to further improve estimations and implement this technology on farms, which should be investigated in the future.

In conclusion, the technology presented in this thesis offers a cost-effective, time-efficient, and labor-saving method for farmers. This non-invasive method can be used on most commercial dairy farms to monitor youngstock growth, improve management practises, and optimize health, reproduction, and milk production. Additionally, the technology can enhance understanding of growth on an individual level and key factors affecting lifetime performance, helping identify best practices and providing clear incentives for their implementation.

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I am delighted to have contributed to such an exciting area of technology and to have gotten to spend time outside of the office and working with the heifers as part of this thesis. This experience has been both professionally rewarding and personally fulfilling.

Finally, a huge thanks to my family and friends for their unwavering support and encouragement throughout this journey.

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Appendix A – Material & Methods

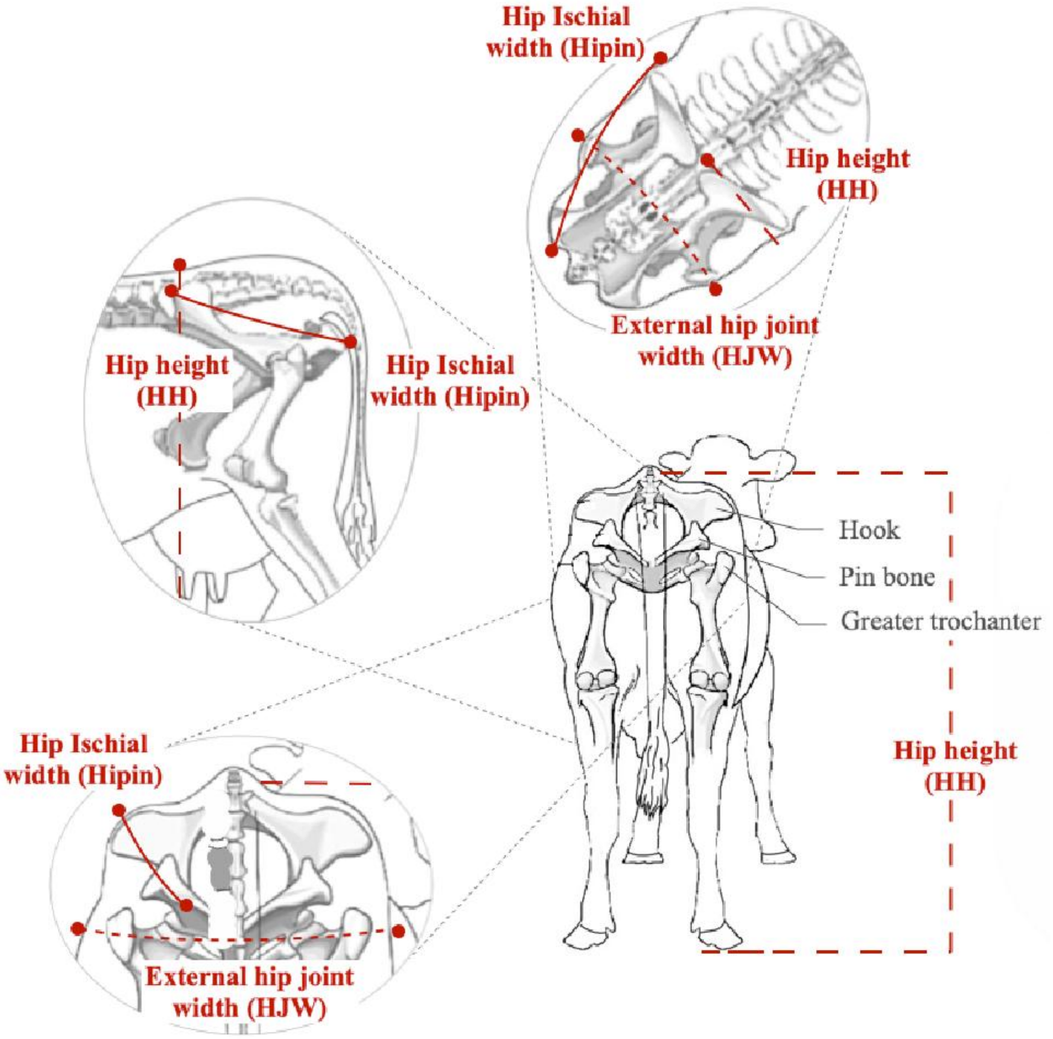

Figure A14Illustration of manual body measurements (BM); hip ischial width (Hipin), hip height (HH), and hipometer, adapted from IMAIOS (n.d.).

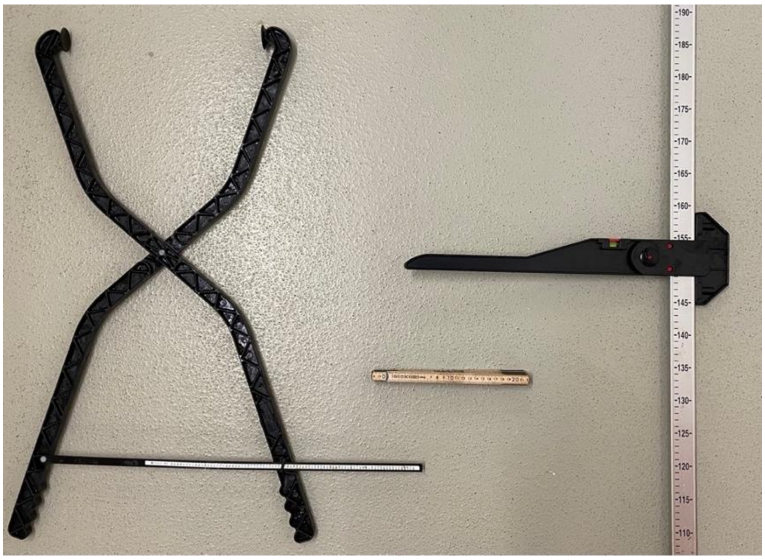

Figure15(A) Height stick with spirit level (cm), (B) measuring stick (cm), and (C) hipometer caliper (kg) (Dairy Innovations, Alexander, NY).

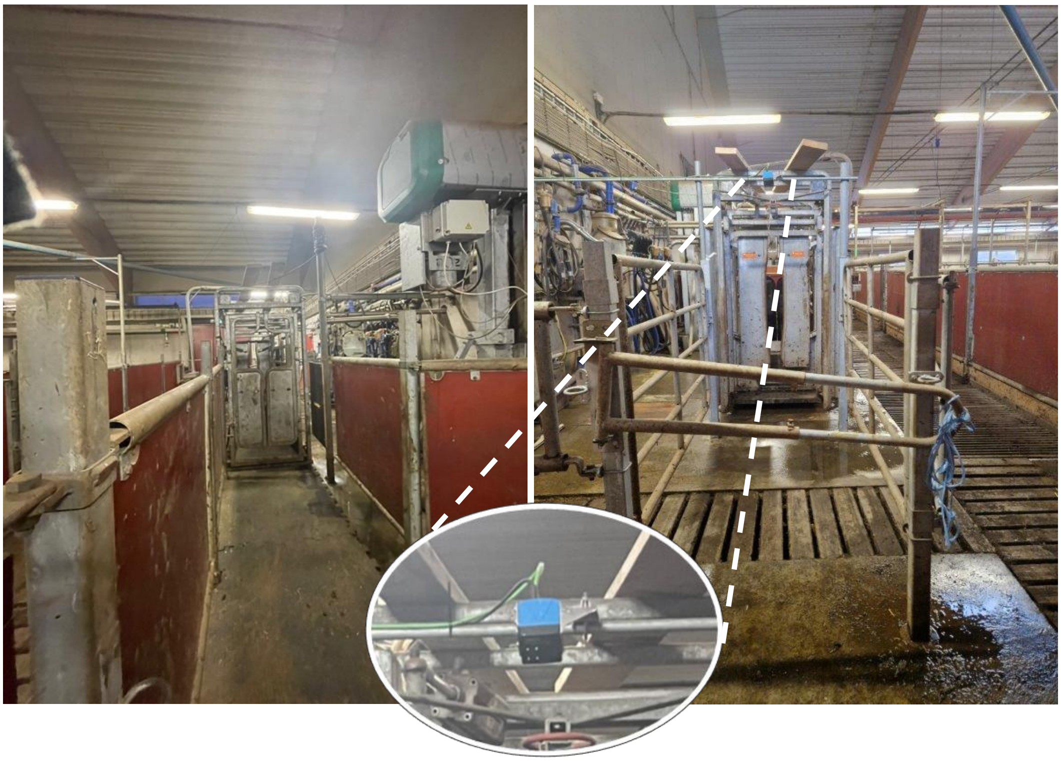

Figure16Entry (left) and exit (right) alleyway from the electronic weighing scale. Enlarged view of the TOF camera (middle).

Appendix B - Results

Table B1. Number of recording days and the total amount of data collection occasions for each measurement – i.e. body weight (BW) and body measurements (BMs) – across all individuals and breeds: Swedish Red (SRB) and Swedish Holstein (SH).

Recording days	**Individuals**	**SRB**	**SH**	**Data collection occasions**
1	6	3	3	6
2	7	6	1	14
3	7	5	2	21
4	4	2	2	16
5	10	7	3	50
6	5	3	2	30
7	13	5	8	91
8	49	28	21	392
Total	**101**	**59**	**42**	**620**

Table B2. Descriptive statistics of all measurements.

Variable	Age group, months	N			Mean			Median			Min			Max		
			SRB	*SH*		*SRB*	*SH*		*SRB*	*SH*		*SRB*	*SH*		*SRB*	*SH*
Weight (BW), kg	All ages	101	59	42	391	379	406	402	368	434	196	198	196	616	616	601
	5 to 7	43	29	14	260	259	262	260	259	261	196	198	196	355	333	355
	8 to 10	45	25	20	361	353	378	358	351	377	290	290	308	470	433	470
	11 to 14	53	25	28	464	451	473	463	445	474	363	363	368	565	560	565
	15 to 17	30	19	11	499	487	526	503	489	529	412	412	433	604	604	567
	18 to 20	3	2	1	585	572	584	578	597	575	565	578	565	616	616	601
Hipometer, kg	All ages	101	59	42	391	383	403	400	374	440	206	206	213	606	606	606
	5 to 7	43	29	14	284	280	293	284	284	289	206	206	213	387	387	374
	8 to 10	45	25	20	375	367	390	374	365	388	265	265	275	502	471	502
	11 to 14	53	25	28	451	428	470	456	430	471	256	256	305	606	569	606
	15 to 17	30	19	11	460	450	481	456	450	502	294	294	441	606	606	569
	18 to 20	3	2	1	520	450	572	531	494	565	413	486	413	588	502	588
Hip ischial width (Hipin), cm	All ages	101	59	42	46	46	47	47	45	49	35	35	37	55	55	55
	5 to 7	43	29	14	40	40	41	40	40	41	35	35	37	45	44	45
	8 to 10	45	25	20	45	45	46	45	45	46	41	41	43	51	49	51
	11 to 14	53	25	28	49	48	50	50	48	50	40	40	44	55	55	55
	15 to 17	30	19	11	51	50	51	51	50	51	46	46	49	55	53	55
	18 to 20	3	2	1	53	54	53	53	54	52	51	53	51	54	54	54

Variable	Age group, months	N			Mean			Median			Min			Max		
			SRB	*SH*		*SRB*	*SH*		*SRB*	*SH*		*SRB*	*SH*		*SRB*	*SH*
Hip height (HH), cm	All ages	101	59	42	132	131	133	134	128	140	110	110	117	150	148	150
	5 to 7	43	29	14	121	119	126	121	118	126	110	110	117	136	128	136
	8 to 10	45	25	20	130	127	136	130	127	136	117	117	128	142	136	142
	11 to 14	53	25	28	139	135	142	140	134	142	124	124	133	148	148	147
	15 to 17	30	19	11	140	137	145	139	137	145	130	130	142	150	146	150
	18 to 20	3	2	1	145	140	147	147	140	148	136	136	145	149	143	149
BCS	All ages (13 to 20)	43	23	20	3,47	3,44	3,50	3,50	3,50	3,50	3,00	3,00	3,00	4,00	4,00	4,00
	13 to 14	35	16	19	3,47	3,43	3,51	3,50	3,50	3,50	3,00	3,00	3,00	4,00	3,75	4,00
	15 to 17	30	19	11	3,45	3,44	3,49	3,50	3,50	3,50	3,00	3,25	3,00	4,00	4,00	3,75
	18 to 20	3	2	1	3,63	3,63	3,75	3,63	3,50	3,63	3,25	3,25	3,50	4,00	3,75	4,00

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