An evaluation study of 3D imaging technology as a tool to estimate body weight and growth in Dairy heifers

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Abstract

The aim of this thesis was to evaluate the use of a 3D camera as a tool to estimate body weight and growth in dairy heifers. Data collection lasted from October 2022 to January 2023 and was performed at the Swedish Livestock Research Centre in Uppsala, Sweden. Data collection included a total of 165 dairy heifers of two breeds: 96 Swedish Red and 69 Swedish Holstein. Body weight, 3D images and a set of nine different body measurements: body length, chest girth, hip width, backside width, ischial width, hip ischial width, withers height, hip height and external width between the hip joints, were collected at six different data collection occasions. All heifers with a full set of manual body measurements and BWs from the scale (n=46) were used in the statistical analysis.

Pearson correlations were used to investigate the relationship between each body measurement and body weight. The highest correlation was found between body weight and chest girth (r = 0.94). The correlation between the body weight and the external hip width (r = 0.91), hip ischial width (r = 0.82) and hip height (r = 0.79) were also among the highest. Body measurements with a correlation ≥ 0.75 (external hip width, hip ischial width, hip width, backside width, hip height, chest girth) were used in the model development together with Point cloud images collected by the 3D camera. Three models, based on data from the 46 heifers with a full data set, were created to predict body weight: 1) a regression model using the manual body measurements as input, 2) a regression model based on the manual body measurements together with the Point cloud image data, 3) a machine learning conventional neural network using the Point cloud image data as model input. The performance of the prediction models were assessed using R^2 and root mean square error (RMSE).

Model 1 showed the best performance among the three models (R^2 = 0.81, RMSE = 17.04 kg). Combining the image data with the body measurements (Model 2) did not improve the model, in fact, lowered the R^2 value (0.41) and increased RMSE (27.13 kg). Model 3 was slightly better than Model 2 with an R^2 value of 0.53 (RMSE = 22.77 kg). Despite the small dataset, the results show potential in creating a model extracting the body measurements from the Point cloud image data rather than only using the point cloud image information. However, not possible to extract body features partly due to the distance between the camera and the heifer, especially for younger heifers with not yet pronounced body features. Several of the previously described and commonly used body measurements were shown to be useful in estimating body weight. Furthermore, the hip ischial width, not described previously, showed a considerably high correlation to body weight and could thus be used in future automatic feature extraction using 3D imaging technology.

Keywords: body measurement, body weight, growth, heifer, youngstock management, 3D imaging

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Abbreviations

AFC	Age at First Calving
BaW	Backside width
BL	Body length
BW	Body Weight
CG	Chest girth
GH	Growth hormone
HH	Hip height
Hipin	Hip Ischial Width
HW	Hip width
ID	Identification number
IW	Ischial width
MAPE	Mean absolute percentage error
MBW	Mature body weight
RMSE	Root mean square error
SH	Swedish Holstein
SRB	Swedish Red Breed

1. Introduction

Raising replacement heifers is an essential part of dairy farm management since the heifers of today will become the dairy cows in the future. Many dairy farmers rear their own youngstock to ensure an adequate supply of replacement heifers. Replacement heifers serve as the second highest contributor to the overall expenses of milk production and is estimated to account for approximately 20% of the total expenditures (Heinrichs, 1993). Efficient rearing systems are crucial as they determine a dairy enterprise future income and sustainability (Mourits *et al.,* 1997). Expenses directly associated with growing heifers, such as feed, labour, reproduction, health and housing (Tozer & Heinrichs, 2001; Brickell & Wathes, 2011) together with the length of the non-producitve rearing period are factors impacting the total costs of raising replacement heifers (Boulton *et al.,* 2017). The non-productive period is determined by the age at first calving (**AFC**) (Brickell *et al.,* 2009). Research shows that it is economically profitable keeping the AFC between 22 and 24 months as it minimises the non-productive period (Mourits *et al.,* 1999; Tozer & Heinrichs, 2001). When comparing how different AFC will affect the rearing costs, Tozer & Heinrichs (2001) found that the rearing costs increased by 14% if the AFC increased to 29 months instead of 25 months. However, not many farms are able to achieve an AFC between 22-25 months, and in Sweden the average AFC is 27 months (Växa, 2022). An important aspect to be able to maintain a lower AFC (22-24 months) is to make sure the animals are of proper body size which requires good heifer management with adequate growth rates (Wathes *et al.,* 2014).

Inadequate growth rates will affect future milk production (Svensson & Hultgren, 2008) as well as overall fertility (Wathes *et al*., 2014). A low growth rate is associated with delayed insemination while a high growth rate may affect conception negatively (Brickell *et al.,* 2009). Good fertility and longevity are both essential for the heifers to reach their full lifetime potential (Wathes *et al.,* 2014). Given the right tools, the youngstock management can be adapted timely to optimize feed intake and thereby also growth rate, feed costs, fertility and longevity.

Growth can be measured in several ways, for example by using different body measurements including BW, chest girth, withers height and hip height (Heinrichs *et al*., 1992). However, most measurements that can be used to record growth are labour-intensive, time-consuming, require training and can be dangerous for both humans and animals. Moreover, it can cause high stress levels to the heifers due to animal handling (Heinrichs *et al.,* 1992; Le Cozler *et al.,* 2022). This contributes to occasional performing of the measurements, which makes it impossible to apply changes in management routines timely. A common practice in commercial farm settings is therefore that decisions regarding the time of first breeding are assessed by visual observation rather than precise weight measurements.

To overcome this problem; vision techniques for youngstock body measurements have been investigated in research settings with promising results (Song *et al.,* 2014), but require improvements regarding image and processing quality (Martins *et al.,* 2020). However, there is insufficient research on growing calves and heifers without any commercial availability today, leaving uncertainties as to what extent the approach can be applied to younstock (Le Cozler *et al.*, 2022). Furthermore, investigations of applications for growing animals are needed as body shape changes troughgout the development (Lobo *et al.*, 2019).

The aim of this thesis was to evaluate 3D camera imaging technique as a tool to estimate BW and growth in dairy heifers. Additionally, data from different body measurements was evaluated as input to models. Furthermore, it was important to understand which body measurement are most highly correlated to BW and what tools are most accurate in estimating BW in dairy heifers.

2. Literature review

2.1 Growth

Growth is a natural process that has an extensive role in animal development. The simplest concept of growth is an increase in body size or BW over time including muscle mass and skeletal structure. Fat deposition in dairy cows will also increase the BW but does not count as growth (Lawrence & Fowler, 2002). In addition, growth is determined by diverse complex factors such as genetics, nutrition, management, health and environment (Heinrichs *et al.*, 1992) and includes multiple aspects: cell, organ, fetal and prepubertal growth among others (Lawrence & Fowler, 2002). Regular monitoring of heifer growth is therefore an important strategy that can help farmers achieve success in raising heifers. Heifer growth can be monitored using different growth indicators such as BW, body condition score (**BCS**) and different body measurements including body length (**BL**), chest girth (**CG**), hip width (**HW**), wither height (**WH**) and hip height (**HH**) (Heinrichs *et al.*, 1992; Wang *et al.*, 2023).

For optimal growth management, the rearing period can be divided into four periods with different suggestions of growth rates depending on the breed of the heifer. The four periods are usually 1) from birth to 3 months of age (the young calf's growth), 2) the prepubertal phase, from 3 months of age to puberty 3) the postpubertal phase, from puberty to conception and 4) the pregnancy period. This categorization is based on the distinct phases of mammary development during fetal life, puberty, pregnancy and lactation (Sejrsen *et al.*, 2000). When planning the feeding for the growing heifers it is therefore important to estimate the growth rate by using growth curves for suitable growth (Sjaastad *et al.*, 2016). Many studies have investigated optimal growth rates during the rearing period using a variety of treatments and growth rates (Drew, 1998; Sejrsen *et al.*, 2000; Herlin & Swensson, 2004; Nilsson, 2009). The optimal growth rate varies depending on breed, calving age, body size at calving and mature body size (Hoffman, 1997). When comparing older Swedish growth standards recommended growth rates of dairy heifers have increased (Herlin & Swensson, 2004; Svensk Mjölk, 2006; Nilsson, 2009) (Table 1). This is mainly due to genetic improvements through breeding and the genetic correlation with milk yield and growth (Nilsson, 2009). Nilsson (2009) states that the growth can be high (900 g/day) during the pregnancy, but that it is important to adapt the feeding during the last months of the pregnancy to avoid overweight heifers at calving.

Table 1. Different suggestions of growth rates during the rearing period (Herlin & Swensson, 2004; Svenska Mjölk, 2006; Nilsson, 2009)

Reference	**Year**	**Breed**	**Target growth rates**[1]		
			0-3	3-13	13-24
Herlin & Swensson	2004	Holstein	700 g/day	700 g/day	700 g/day
Svenska Mjölk	2006	Holstein	700 g/day	750 g/day	800 g/day
		SRB	650 g/day	700 g/day	750 g/day
Nilsson	2009	Holstein	900 g/day	750-800 g/day	900 g/day[2]

[1]Age in months, [2]13-20 months

2.1.1 The young calf's growth

The growth rate during the calf's first two to three months of life is of great importance for the calf´s future conditions as a milk producing dairy cow. During this period, the calves are generally fed milk with different volumes depending on milk feeding strategy at the specific farm, calf age and BW. A common feeding strategy is to feed the calves with 10% of their BW at first feeding (Jasper & Weary, 2002). Compared with other stages of heifer development, the calves have the ability for the highest lean muscle growth (Akins, 2016) and grows the fastest in relation to their body size (Nilsson, 2009). During these first months of life, the mammary gland develops at the same rate as the rest of the body (*isometric growth*) and it is therefore an advantage if the calf´s growth potential is utilized to the maximum (Sejrsen *et al.*, 2000). For young calves, the primary source of daily weight gain should be muscle and skeletal growth with minimal fat deposition, which is highly dependent on the feeding rates (Akins, 2016). Optimal growth rate is widely discussed with different opinions about how much the calves should grow. According to Akins (2016), the goal should be to double the calf´s weight until the weaning when the weaning takes place from six to eight weeks. Bazeley *et al.* (2016) reported that the recorded birth weight showed no significant correlation to growth rate at 42-78 days of age. Although, heavier birth weight were found to have a significant association with the expected weight at 60 days, which is a key stage of development (Bazeley et al. 2016).

2.1.2 The prepubertal period

The basic structures of the mammary glands are formed already in fetal life. However, it is not until about 3 months of age that the epithelial tissue in the udder starts to grow as a result of the mammary glands growing at a faster rate than the rest of the body (*allometric growth*) (Serjsen *et al.*, 2000; Nilsson, 2009). During this period, the development can be affected by nutrition and multiple studies have reported that when fed high-energy diets (excess energy) promting rapid BW gain during the prepubertal period, additional adipose tissue will deposit in the mammary gland (Sejrsen & Purup, 1997; Sejrsen *et al.*, 2000; Ettema & Santos, 2004). Additional adipose tissue in the mammary gland is in turn associated with subsequent milk production of dairy heifers (Sejrsen & Purup, 1997; Ettema & Santos, 2004). The relationship between heifer growth and future milk production is complicated, but a meta-analysis of eight studies concluded that Holstein heifer growth should be limited to 800 g/day, during this period, for maximal first lactation milk production (Zanton & Heinrichs, 2005).

2.1.3 The postpubertal period and pregnancy period

After the prepubertal period, the udder growth returns to isometric growth (Sjaastad *et al,*. 2016) with an exception during the last part of pregnancy (Sejrsen *et al.*, 2000). Studies have shown that high growth rates during this period will not affect the future milk production negatively (Sejrsen *et al.*, 1982, 2000; Drew, 1998).

The majority of the mammary growth occurs during the pregnancy with a remarkably increase of the udder size during the last three to four months (Sjaastad *et al.*, 2016). The growth is dependent on simultaneously elaveted concentrations of estradiol and progesterone in the blood (Sjaastad *et al.*, 2016), which happens for a short period during each oestrus. During pregnancy the placenta is maintaining high estradiol and progesterone and a voluminous growth of the mammary tissue starts. Feeding strategies for the pregnant heifer should meet target growth rates to ensure adequate calving weights. In 1998 it was put forward that growth rate in prepubertal pregnant heifers should be no more than 600 g/day (Drew, 1998). However, there are now increasing stories from farms that apply non-restricted growth rate which also seems to work.

2.2 Fertility

High fertility plays a significant role in the efficiency of a dairy enterprise and is characterized by heifers reching puberty, and both heifers and older cows coming into heat and becoming pregnant. Puberty in heifers is defined as the time when they has their first ovulation and start showing a heat period (Bailey & Murphy, 2009). After the initial ovulation, the heifer should go into heat continuously and for cattle, the estrous cycle typically lasts for 21 days (Sjaastad *et al.*, 2016). According to Sejrsen & Purup (1997), onset of puberty generally occurs when the heifers are between 9-11 months old. However, onset of puberty is also greatly influenced by the BW (Sejrsen & Purup, 1997). Dairy heifers usually achieve puberty after reaching between 40-50 % of their predicted mature BW (Bailey & Murphy, 2009; Heinrichs & Jones, 2016). Sejrsen & Purup (1997) reported that the majority of heifers reach puberty between 200-300 kg with less than 5 % reaching puberty before 200 kg and less than 10% reaching first estrus after reaching 300 kg.

Fertility is a critical component of AFC, which in turn is an important determinant of performance within the herd (Wathes *et al.*, 2014). An AFC between 22-24 months of age is shown to be optimal (Mourits *et al.*, 1999; Tozer & Heinrichs, 2001; Ettema & Santos, 2004; Brickell *et al.*, 2009). Heifers with a higher AFC have shown to produce more milk during the first lactation, which was explained by higher BW (Ettema & Santos, 2004). Research by Dobos *et al.* (2001) showed that the BW at first calving is 2-3 times more important than the age to get a optimal milk yield during the first lactation. Both age and BW is important for the later lactations (Dobos *et al.*, 2001) and high AFC is associated with a shorter productive life due to fewer milk producing days (Nilforooshan & Edriss, 2004). In addition, high AFC will increase the feed and management expenses compared with a lower AFC (Nilforooshan & Edriss, 2004). Another important consideration is that AFC may influence the risk of dystocia, also known as calving difficulties (Ettema & Santos, 2004; Herlin & Swensson, 2004; Wathes et al. 2014). Dystocia is related to the BW at first calving and Ettema & Santos (2004) reported a negative correlation between BW at calving and dystocia, meaning that younger, smaller heifers have an increased risk of experiencing dystocia. Moreover, research have also found an increased risk for dystocia with an AFC above 25 months (Herlin & Swensson, 2004), which most likely is due to the increased risk for overweight heifers with increasing AFC (Wathes *et al*., 2014). This underlines the importance of making sure that heifers have reached an adequate size and BW before the first calving (Ettema & Santos, 2004).

2.3 Body weight

2.3.1 Factors affecting body weight

In heifer rearing, many decisions can be based on BW; estimating the appropriate breeding weight, nutrient requirement and overall management (Martins *et al*., 2020). BW of heifers is affected by multiple factors including growth, fertility, pregnancy and gut fill (Hoffman, 1997). In addition, other factors such as time of day, feeding and watering can affect the accuracy of the weight measurements (Davis & Hathaway, 1955). All animals have an innate mature body size at which they grow at a genetically controlled rate (Heinrichs & Hargrove, 1987). Depending on environmental factors, the growth can either proceed constantly or vary over time with differences both between and within breeds (Swanson, 1966; Sejrsen & Purup, 1997).

2.3.2 Body measurements as a marker for body weight

The simplest and most accurate approach is to weigh the heifers in a calibrated electronic scale (Dingwell *et al*., 2006). Ideally, the weighing of calves and heifers is done regularly. However, scales are expensive, labour-intensive and time-consuming and alternative methods of BW estimation would therefore be beneficial (Heinrichs *et al*., 1992).

Using different body measurements, also named morphological traits, is an alternative method that can estimate the BW and simplify the understanding of heifer growth (Heinrichs *et al.*, 1992). One of the most common methods is to use a weight tape, which allows quick estimation of the heifers BW by measuring the circumference of the chest (heart girth) (Heinrichs *et al.,* 1992). Research has shown a high correlation between the heart girth and the BW (Davis *et al.*, 1961; Heinrichs *et al.*, 1992) with an accuracy within 3-5% of the actual BW for heifers over 150 kg (Heinrichs & Jones, 2016). In addition, the method has shown to have little variation in repeated measurements both when performed by an individual or by multiple people (Heinrichs *et al.*, 2007).

Other body measurements including BL, HW, HH and WH, can also be used to measure or estimate BW (Heinrichs *et al.*, 1992). All these body measurements are indicators of skeletal growth (Heinrichs *et al.,* 1992) with prominent anatomical locations that are relatively easy to identify when measuring the animals (Enevoldsen & Kristensen, 1997). Heinrichs *et al.* (1992) investigated the relationships between BW and different body measurements including HG, BL, WH and HW. They performed linear regressions on BW based on the different body measurement which showed that heart girth had the highest correlation with BW, followed by HW. Although, each measurement were found to be useful in predicting BW ($R^2 > 0.95$) (Heinrichs *et al.*, 1992).

In other research, evaluation of the weight tape and the hipometer were performed (Dingwell *et al.,* 2006). The hipometer is a more recent indirect tool that estimates BW by measuring the external width between the hip joints (Dingwell *et al.,* 2006). The hipometer consists of two arms that cup over the greater trochanters of the femurs and based on the width of the caliper arms, BW can be estimated (Dingwell *et al.*, 2006). They found very high correlation coefficients when comparing the weights from the scale with the weights for both the hipometer and the heart girth tape. Therefore, they concluded that both methods are useful alternative methods of estimating BW (Dingwell *et al.*, 2006). However, there are disadvantages with both methods; difficulties to perform consistently if there are body movements of the heifers and risk of improper amount of pressure when using the hipometer (Dingwell *et al.*, 2006). In addition, the authors emphasize that the hipometer is shown to be less accurate for animals younger than 3 months and older than 15 months. Obtaining growth rates demands a lot of measurements which is very time-consuming and labour-intensive. Similar to weight scales, most body measurements are also subjective and there are risks coming with handling the heifers which can cause stress for both the heifers and farmers (Heinrichs *et al.*, 1992; Le Cozler *et al.*, 2022).

2.3.3 Automatic estimation of body weight

To overcome the limitations of conventional measurement systems, research has investigated the possibility to use new technologies, such as vision in combination with machine learning, to estimate BW (Song *et al.*, 2014; Le Cozler *et al.,* 2019b; a; Martins *et al.*, 2020). Using vision tools requires image collection and analysis which can be done with two-dimensional (**2D**) and three-dimensional (**3D**) vision systems (Song *et al.*, 2014). These techniques have multiple advantages which can reduce the distress caused by manual measurements; less time-consuming non-contact system with more accuracy and objectivity (Wang *et al*., 2023) and more frequent registrations than when done manually. In addition, the methods can be used for several purposes and have been developed to detect lameness in dairy cows (Van Hertem *et al.*, 2014), automate BCS (Bewley *et al.*, 2008; Anglart, 2010) and predict BW using automatic estimation of different body measurements (Song *et al.,* 2018).

Segmentation is an important part for preprocessing of images to be able to correctly differentiate the animal from its background. This has showed to be difficult for 2D images with factors such as changing light conditions, shadows and backgrounds affecting (Salau *et al.*, 2015). Therefore, in recent years, 3D cameras have increased in popularity and demonstrated a good possibility for use in dairy farms. The most commonly used technology for 3D cameras is the time of flight (ToF) technology (Song *et al.*, 2014), which uses visible or near-infrared (NIR) light to estimate full-range distance information. Smart pixel sensors in the camera measures the return time for the reflected light to illuminate the object being imaged (Lindner *et al.*, 2010).

Martins *et al.* (2020) investigated the possibility to automatically determine BW with the use of 3D cameras from two perspectives; dorsal (top view) and lateral (side view). The obtained models to estimate BW had an R^2 of 0.96 and 0.89 and RMSE of 26.89 and 49.20 for dorsal and lateral perspectives, respectively, which indicates that both perspectives can be used for BW estimation (Table 2). Several other studies have also investigated the possibility to automatically estimate BW based on biometric body measurements, morphological traits, surface areas or volumes (Anglart, 2010; Kuzuhara *et al.*, 2015; Hansen *et al.*, 2018; Song *et al.*, 2018; Le Cozler *et al.*, 2019b, 2022; Xavier *et al.*, 2022) (Table 2).

2.4 Economical aspects

With replacement heifers being the second highest contributor to the overall expenses of milk production (Heinrichs, 1993), the economical aspects are important to keep in mind to be able to have a profitable dairy production. The rearing period is non-productive with multiple high-cost components including feed, labor, reproduction, health and housing (Tozer & Heinrichs, 2001; Brickell & Wathes, 2011; Heinrichs & Jones, 2016). These costs varies between farms depending on different management strategies and environmental aspects (Heinrichs *et al.*, 2022). However, the associated expenses are often hidden with no return until the heifers enter the milking herd (Boulton *et al.*, 2017). In addition, dairy cows have an average productive lifespan between 2.5-4 years meaning that half of their lifespan is spent as non-productive growing heifers (Heinrichs & Jones, 2016). Therefore, it is important to balance the inputs with the delayed return which highlights the importance of adequate growth, fertility and BW (Heinrichs & Jones, 2016).

Table 2. Research work on automatic body weight estimation for dairy cows and heifers in recent years (2010-2022).

Reference	**Approach**	**Model**	**Breed**	**Nr of animals**	**R**	**R^2**	**RMSE (kg)**	**MAPE (%)**
Anglart (2010)	3D	Artificial neural networks	SH, SRB (cows)	70	0.87	-	-	-
Kuzuhara *et al.* (2015)	3D	Linear regression	Holstein (cows)	8	0.893	0.80	42.65	-
Song *et al.* (2018)	3D	Multiple linear regression	Holstein (cows)	30	-	-	41.2	5.2
Hansen *et al.* (2018)	3D	Regression analysis	Holstein (cows)	185	-	-	-	11
Le Cozler *et al.* (2019b)	3D	Linear regression	Holstein (cows)	64	-	0.93	-	-
Martins *et al.* (2020)	3D	Statistical analysis	Holstein (cows + heifers)	55	-	0.96[1] 0.89[2]	26.89[1] 49.20[2]	-
Xavier *et al.* (2022)	3D	Linear regression	Holstein (cows)	16	-	0.92	25.4	-

[1]Dorsal perspective, [2]Lateral perspective, [*]R = correlation coefficient; R^2 = coefficient of determination ; RMSE = root mean squared error; MAPE = mean absolute percentage error

3. Materials and Methods

3.1 General aspects

The study was carried out between October 2022 and January 2023 at Lövsta Swedish Livestock Research Centre, Uppsala, Sweden. Lövsta manage their own recruitment, which means that no animal is bought into the herd and that the animals are used to the environment.

3.2 Animals and housing

The animals used in this study consists of two breeds; Swedish Red (SRB) and Swedish Holstein (SH). The study included 165 heifers of SRB (n=96) and SH (n=69) at ages 6-15 months when data collection started. The heifers were kept in a loose housing system, divided into five units according to age. The youngest heifers were housed in unit one and the oldest heifers were housed in unit five. During the study period, the heifers were moved between the units depending on increasing age and weight. Data could only be collected in units 1 and 5 meaning that when heifers moved into unit 6 they were lost from the data collection (Table 3). The table displays the total number of heifers included at each data collection occassion. The mean birth weight and mean weaning weight for the heifers was 38 kg and 126 kg, respectively. The heifers were fed silage *ad libitum* and had free access to fresh water. The heifers in unit 1, which were between 6-10 months old, were also fed approximately 2 kg concentrate per heifer and day during the whole study period.

Table 3. Overview of the distribution of the number of heifers, breed and age in the five units during the six data collection occasions

Data Collection		Unit 1	2	3	4	5	Total
1	Nr of heifers	21	25	25	23	42	136
	Breed SH	8	8	10	13	17	56
	Breed SRB	13	17	14	12	25	80
	Age (mo)	6-8	7-15	8-12	9-13	14-18	
2	Nr of heifers	23	27	24	24	42	140
	Breed SH	9	10	10	12	17	58
	Breed SRB	14	17	14	12	25	82
	Age (mo)	6-8	8-15	9-12	10-14	14-19	
3	Nr of heifers	28	21	24	23	38	138
	Breed SH	10	9	11	14	14	58
	Breed SRB	18	12	13	9	24	80
	Age (mo)	7-10	8-9	8-14	10-14	14-18	
4	Nr of heifers	20	22	43	*	38	123
	Breed SH	9	8	21	*	16	54
	Breed SRB	11	14	22	*	22	69
	Age (mo)	6-7	7-8	8-16	*	12-19	
5	Nr of heifers	19	22	43	*	37	121
	Breed SH	7	8	21	*	15	51
	Breed SRB	12	14	22	*	22	70
	Age (mo)	6-7	7-9	8-16	*	15-19	
6	Nr of heifers	21	27	44	*	32	124
	Breed SH	5	12	21	*	16	54
	Breed SRB	16	15	23	*	16	70
	Age (mo)	7-8	8-11	10-17	*	14-19	

*Unit 3 and 4 were together in one big unit from data collection 4 to 6.

3.3 Study design

BWs, 3D images and body measurements were collected at each data collection. BW and 3D images were collected for all heifers in unit 1-5 while the body measurements were collected for as many heifers as possible in the same five units, with time being the limiting factor. The data collection were conducted during a total of six data collection occasions: October (19th), November (3rd and 17th), December (1st and 12th) and January (13th). Once a month, the data collection occasion corresponded to the monthly performed weighing for the farm.

3.3.1 Body weights

At the beginning of each data collection occassion, BWs were collected for all heifers in a electronic (PM 2855) cattle weighing crush (Marechalle-Pesage Livestock weighing crushes, Chauny, France). Pictures of the scale can be found in Figure 9, Appendix. The heifers entered the scale one at a time; the exit gate was closed to ensure that the heifer would stay in the scale, and the entrance gate was closed behind her as she stepped in. Once the heifers was in the scale, the heifer was identified by an EID reader that sent the heifers identification number (**ID**) to a weighing indicator (TRU-Test EW6), which was attached to the weighing scale. The weighing of the animals took about two hours and the weights were usually collected between 8.00 am and 10.00 am. After the weighing, the heifers were sent back to their respective unit in the loose housing system. The weights were stored together with the ID of each heifer and the timestamp of when the weight was recorded. This information were unknown until the day after the collection day to prevent bias.

3.3.2 Image data collection

As the heifers exited the weight scale, 3D images from a full body top view were recorded with a TOF 3D camera. The camera was placed facing horizontal to ground without any inclination at a height of 240 cm in the isle leading from the weighing crush (PM 2855) and back to the housing units. The camera was connected directly to a computer via an ethernet port (Figure 1) and triggered automatically when it identified a cow object in the frame. The heifers were stopped on the scale for a few seconds which was necessary for the weighing and a slow exit to ensure that one heifer at a time was under the camera during the recording. The camera installation was provided by DeLaval International AB, Tumba, Sweden.

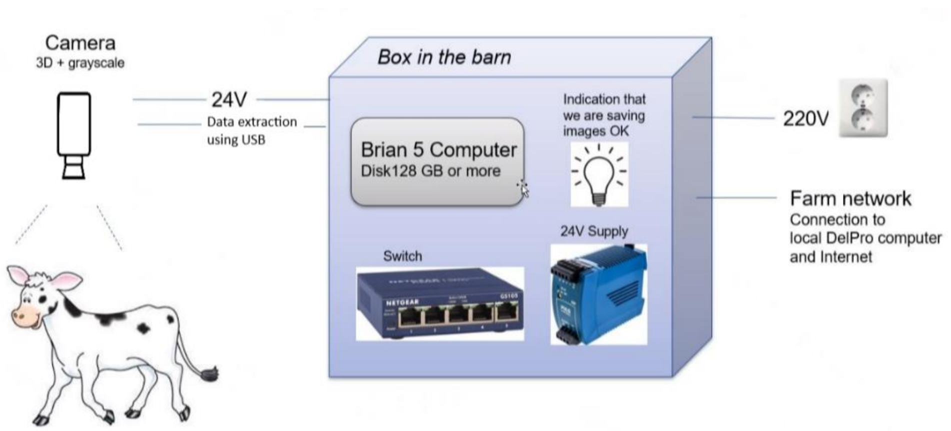

Figure 1. The installation of the 3D camera and the computer

The images from the 3D camera were saved once the heifer entirely entered the frame. The data collected from the 3D camera were Point cloud images (X, Y and Z), which contain the distance values from the camera to the heifers' back. Each pixel in the image represents the distance value (*mm*) from the camera to the point cloud of the heifer. Additionally, intensity images (i.e., normal greyscale image) were saved for each heifer (Figure 6). All images were saved together with the timestamp of when the photo was taken. Since the 3D camera was placed directly after the weighing scale, animal numbers could be matched to the timestamp from the weight scale.

Data selection

The image data from the 6th data collection (13th of January) were excluded as the images were corrupted for unknown resason. All heifers with full set of the manual body measurements and BWs from the scale that were found among all 5 remaining trials (n=46) were selected for the model training.

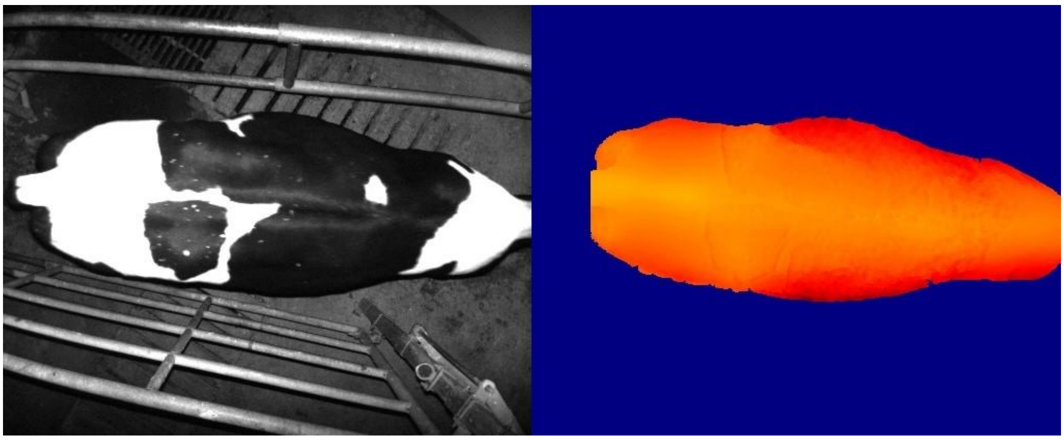

Figure 2. Intensity image from the 3D camera (left) and the Point cloud image (right)

3.3.3 Body measurements

Once the heifers were back in their respective housing units, collection of nine different body measurements were taken on as many heifers as possible; CG, BL, HW, BaW, IW, Hipin (Figure 3), WH, HH and the width between the hip joints (Figure 10, Appendix). Before starting the body measurements in each group, the heifers were put in a looking head gate at the feeding table.

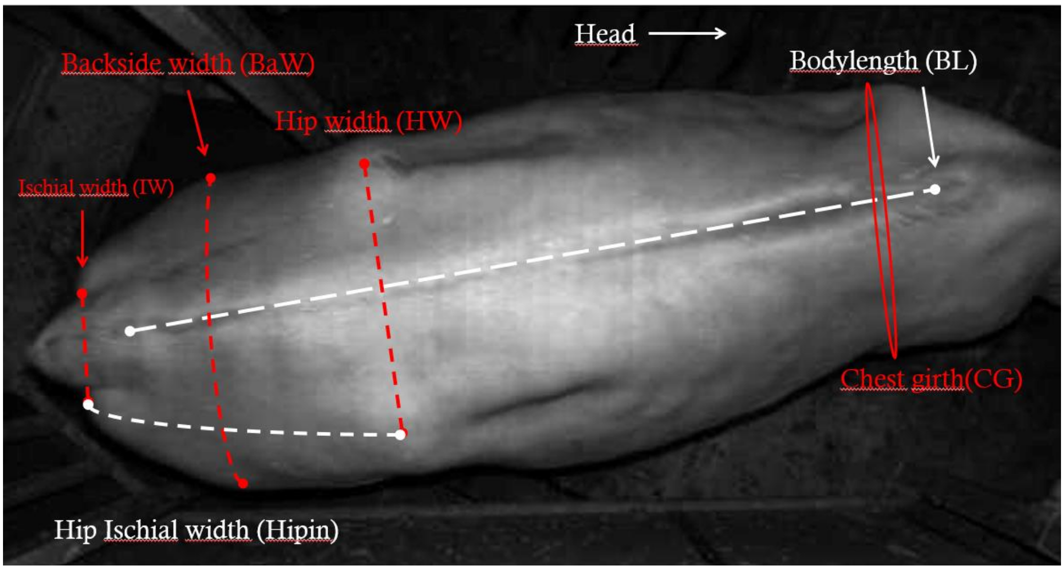

Figure 3. How the body measurements were performed

All body measurements were performed by the same two people during the whole study period. The collection of the body measurements usually took between four to six hours. Four different measuring tools were used for the body measurements; a measuring tape (cm), a Coburn Weight-By-Breed Dairy Cow tape (cm and kg) (The Coburn Company, Inc., Whitewater, WI), a hipometer caliper (kg) (Dairy Innovations, Alexander, NY) and a sliding-scale height stick (cm) with a spirit level (Figures 4-5). A detailed description of how each measurement was performed and equipment used for each measurement can be found in table 4. When using the hipometer, the forcep-like arms on the hipometer were cupped over the greater trochanters of the left and right femurs of the heifer. In the beginning of each data collection, a calibration rod were used with the hipometer to ensure that appropriate amount of pressure were placed on the calipers. The width of the opening of the caliper arms translates to a weight which were recorded directly from the sliding scale of the hipometer (Figure 4B). The gradiation of the caliper arms on the hipometer ranged from 32-750 kg. The gradiation of the height stick (Figure 4C) ranged from 105 cm to 190 cm.

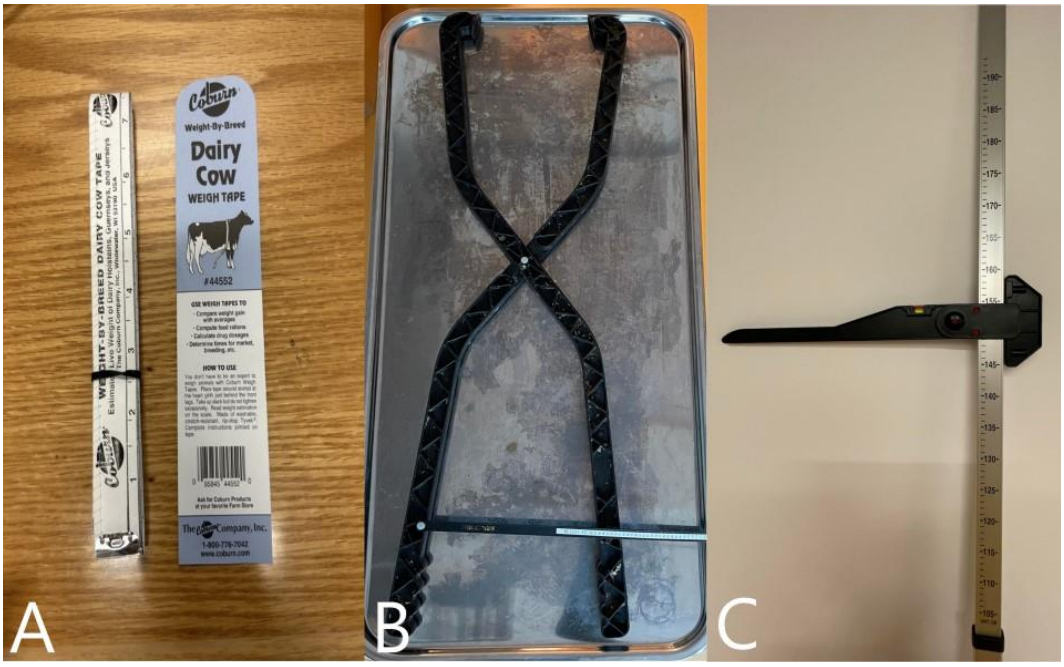

Figure 4. A) Weight-By-Breed tape (The Coburn Company, Inc., Whitewater, WI), B) Hipometer caliper (Dairy Innovations, Alexander, NY), C) Sliding-scale height stick with spirit level

Figure 5. Close up on the height stick with spirit level

Table 4. Detailed description of body measurements, how each body measurement was performed and what equipment was used

Body measurements	**Description**	**Equipment**
Chest girth (CG)	The smallest circumfence of the heifer when measured just behind the front legs.	Measuring tape[1] Weight-By-Breed tape[2]
Body length (BL)	The horizontal distance from the point of the shoulders to the start of of the tail bone.	Measuring tape[1]
Hip width (HW)	The distance between the two hook bones. Measured over the back of the heifer.	Measuring tape[1]
Backside width (BaW)	The distance between the greater trochanters of the left and right femurs. Measured over the back of the heifer.	Measuring tape[1]
Ischial width (IW)	The distance between the pin bones. Measured over the tail.	Measuring tape[1]
Hip Ischial width (Hipin)	The distance between the hook bone and the pin bone. Measured from one side of the heifer.	Measuring tape[1]
Wither height (WH)	The distance between the surface the heifer is standing on with front legs to the highest point of the shoulder.	Height stick[1]
Hip height (HH)	The shortest distance between the surface the heifer is standing on with back legs to the top of the spine between the hips.	Height stick[1]
Width between the hip joints	Measured on the greater trochanters of the left and right femurs. Measured straight behind the heifer.	Hipometer[2]

[1] Unit in cm, [2] Unit in kg

3.4 Statistical analysis

The manually collected measurement data were analysed using Persons correlation to investigate the relationship between each body measurement and the BW. The data on the body measurements that had a correlation ≥ 0.75 with the BW (Hipometer, Hipin, HW, WH, BaW, HH, CG) were used for model training together with the Point cloud images collected by the 3D camera. Three types of statistical models were created: 1) regression model based on the manual body measurements, 2) regression model based on the manual body measurements together with the Point cloud image data 3) a machine learning conventional neural network with the Point cloud image data as input to the model. Due to the small sample size, for each model, heifers were handpicked and assigned into different train data set (n = 33) and test data set (n = 13) to get good distribution of the BW. The output from all models were BW of the animal in kg. The modelling was performed by engineers at DeLaval International, Tumba, Sweden. Growth was analysed using box plots and by calculating the growth rate between each data collection.

4. Results

4.1 Body weights

A total of 776 BW records were obtained during the data collection period, and each individual heifer was weighed between 1 and 6 times (Table 5). The lowest and highest weights recorded were 174 kg and 575 kg, respectively. The highest frequency of BW was found in the weight range of 300-400 kg which follows a normal distribution. The mean BW was 357.7 kg.

Table 5. Number of weighings for individual heifers.

Number of times an animal was weighed	**Number of unique animals**	**Total number of weighings**
1	15	15
2	10	20
3	24	72
4	5	20
5	17	85
6	94	564
Total	165	776

The distribution of all recorded BWs during the study is presented in Figure 6. In total, 324 BWs were recorded for SH and 452 BWs were recorded for SRB. The growth in terms of BW seems to decrease in the age interval between 9 and 12. The variation in BW was overall larger for the SRB than for SH. Within the age interval between 18 and 19 months, in total only 38 measurings were available.

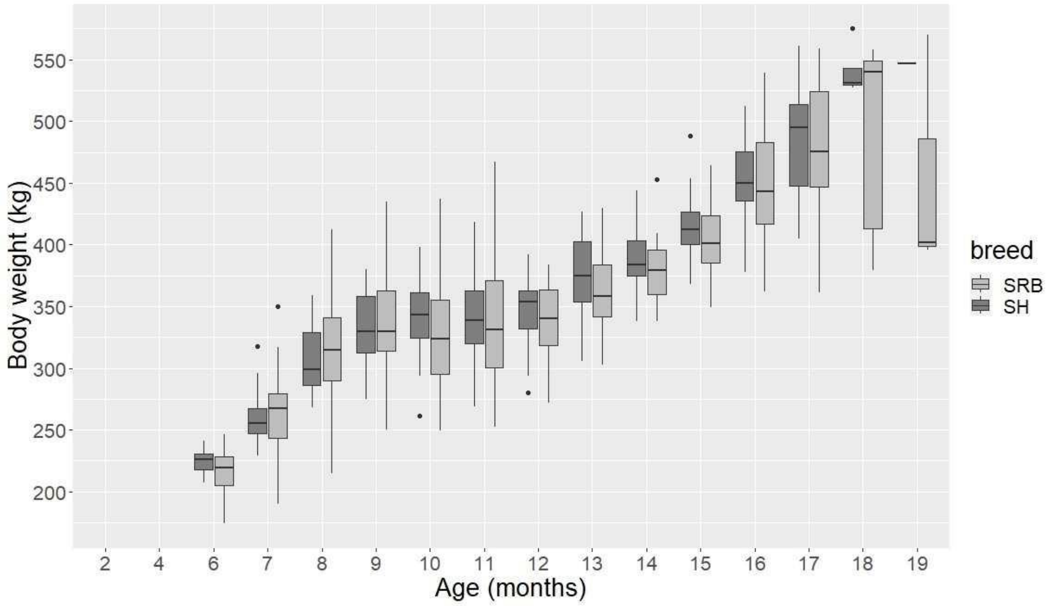

Figure 6. Boxplot demonstrating the distribution of body weights for both breeds in different ages in months during the study.

4.1.1 Relationship between body measurements

The body measurements were performed on a total of 156 dairy heifers during the 6 data collections. Out of these heifers; 50 were measured during four occasions, 48 were measured during five occasions and 26 were measured during all six occasions.

Pearson correlations were performed to investigate the relationship between each body measurement and the BW. Body weight was highly correlated with several of the nine body measurements (Table 6). The highest correlation coefficient was found between BW and CG, both measured in cm and kg (r = 0.94). The correlation between BW and the hipometer was also high (r = 0.91), as well as the Hipin (r = 0.82) and HH (0.79) measurements. Considering breed differences, only a small difference could be found. For instance, Hipin had slightly higher correlation to BW for SH (r = 0.85) compared with SRB (r = 0.80). The mean estimated BW was 331.8 kg and 331.0 kg for the hipometer and the CG tape, respectively.

Additional information about the number of animals each collection together with the number of animals that got body measurements taken including breed, age and BWs can be found in Table 8, Appendix. Descriptive statistics of the collected variables can be found in Table 9, Appendix.

Table 6. Pearson correlation coefficients between body weight and the measured variables or other animal information available.

		Breed	
Body trait	**Pearson correlation**	**SH corr**	**SRB corr**
Weaned weight, kg	0.02	-0.02	0.05
Birth weight, kg	0.28	0.29	0.27
Ischial width (IW)	0.51	0.45	0.56
Body length (BL)	0.68	0.68	0.69
Hip width (HW)	0.75	0.73	0.76
Wither height (WH)	0.75	0.84	0.83
Backside width (BaW)	0.79	0.77	0.80
Hip Height (HH)	0.79	0.87	0.84
Hip Ischial pin (Hipin)	0.82	0.85	0.80
Age, month	0.84	0.87	0.81
Hipometer, kg	0.91	0.92	0.91
Chest girth, cm (CG)	0.94	0.96	0.95
Chest girth, kg (CG)	0.94	0.96	0.95

4.1.2 Growth

The growth rate was calculated as % increase in BW of each heifer between the data collection occations (Figure 7). Both the highest as well as the lowest growth rate was observed in the SRB. The maximal growth rate was found to be 16% at the age of 7 months while the lowest growth rate was found to be -10% at the age of 8 months. During the first months recorded (5-7), there is only increase in growth while negative growth rates (lack of growth or error in measurements) was found between age 8-12 and 15 for both breeds. For SH, negative growth were also present at the age of 13 and 16 months.

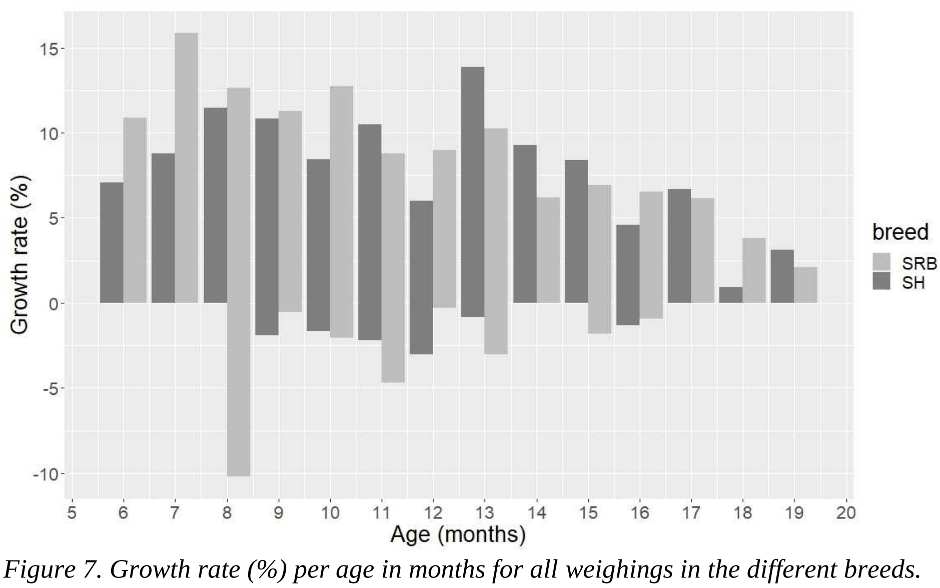

Figure 7. Growth rate (%) per age in months for all weighings in the different breeds.

4.2 Image data collection

The results for Model 1 showed a R^2 value of 0.81 and an RMSE of 17.03 kg. Combining the image data with the body measurements (Model 2), did not improve the model, and the R^2 value was lower (0.41) with a higher RMSE (27.13 kg). Model 3 was slightly better than Model 2 with an R^2 value of 0.53 (Table 7).

Table 7. Results from the statistical models including the R^2 and root mean square error (RMSE), where Model 1 was based on body measurement data, Model 2, a combination of body measurements and image analysis and Model 3, image analysis alone.

Models	R^2	RMSE
1	0.81	17.04 kg
2	0.41	27.13 kg
3	0.53	22.77 kg

Regression plots of true vs. predicted BWs from the three models are shown in Figure 8. All three models displayed a positive linear relationship between true and predicted BW. For Model 1, smaller variation was found compared to the other two Models. The variation was largest for Model 2, which over- and underestimated the predicted BW.

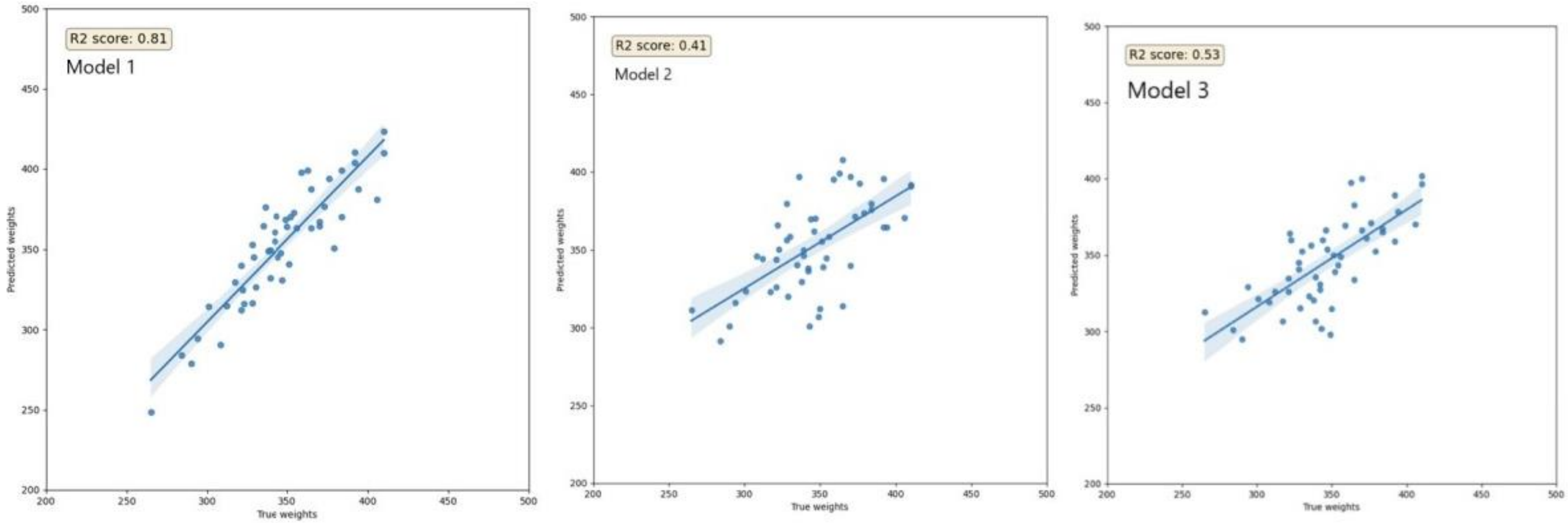

Figure 8. Regression plots of true vs predicted body weights (kg) in Model 1-3. Model 1) Body measurements, Model 2) Body measurements + Point cloud image data, Model 3) Point cloud image data

5. Discussion

The manual collection of body measurements was important for understanding which body measurement correlated to BW and what tool had highest accuracy estimating BW in dairy heifers. Our findings were in accordance with previous studies estimating BW using CG as a proxy where CG has shown to be more accurate than other measurements (Davis *et al.,* 1961; Heinrichs *et al.,* 1992) with correlations from 0.82 to 0.92 (Mäntysaari & Mäntysaari, 2008; Yan *et al*., 2009; Gruber *et al*., 2018; Tebug *et al*., 2018). The highest correlations found were between the BWs recorded by the scale and the BWs estimated from the CG tape (r = 0.94) and the hipometer (r = 0.91), respectively (Table 6). These results agree with previous work by Dingwell *et al.* (2006) that found correlations of 0.94 and 0.92 for the CG tape and HW measured by the hipometer, respectively. Dingwell *et al.* (2006) performed the measurements on Holstein heifers, while this study included heifers of two breeds; SH and SRB. When breeds were analysed separately, the correlations were still high and similar across breed (SH = 0.96, SRB = 0.95). Using the hipometer, proper calibration is important to ensure that the appropriate amount of pressure is applied (Dingwell *et al.*, 2006). In our study we used the calibration rod before each data collection to verify and confirm the amount of pressure needed, and the results concur with those from the author mentioned above.

As of today, no previous studies have reported or included the hipin measurement. The results showed a considerably high correlation (r = 0.82). The correlation was slightly higher for the SH (r = 0.85) compared with the SRB (r = 0.80). The measurement was taken between the hook bone and the pin bone, which are two prominent bones that are fairly easy to identify when standing next to the heifers (Enevoldsen & Kristensen 1997). HH showed slightly higher correlation to BW (r = 0.79) compared with WH (r = 0.75). Height-related features in younger animals are indicators of early development and BW gain (Heinrichs *et al.*, 1992). Previous studies state that hip height can be performed without much consideration about the head placement of the animal, compared with the wither height (Heinrichs & Jones, 2016), which can be a reason obtaining these results.

BW estimation is of great importance during different phases of the animals growth with weighing in a electronic scale being the most accurate approach (Dingwell *et al.*, 2006). In the current study setup, the research farm was equipped with a stationary electronic scale used monthly to weigh the growing heifers. However, among conventional farms it is not regular practice to measure growth using electronic scale due to limitations of space, time or the economy to invest in a electronic scale (Heinrichs *et al.*, 1992). Therefore, it is important to have alternatives to be able to frequently estimate BW and growth of heifers for management purposes. Less accurate and cheap methods such as the body measurements investigated in this study could be utilized and of great value. However, they are manual, labour-intensive and time-consuming. All together, collecting data on the nine body measurements took between four and six hours to perform at each data collection occaction (measuring between 66 and 109 heifers). One body measurement would be enough in a conventional setup. However, manual measurements could influence the growth of the heifers negatively because of animal handling and stress (Heinrichs *et al.*, 1992). Although, neither extreme growth or extreme lack in growth were found in this study (Figure 6). In addition, the manual body measurements requires close contact with the heifers, which can be dangerous for the people performing the measurements. Therefore, tools such as a 3D camera, that could automatically estimate the BW and thereby also growth due to the possibility of frequent estimations, is an interesting option.

Previous studies have investigated the prospect of estimating BW by 3D imaging in dairy cows (Anglart, 2010; Kuzuhara *et al.*, 2015; Hansen *et al.*, 2018; Song *et al.*, 2018; Le Cozler *et al.*, 2019b; Martins *et al.*, 2020; Xavier *et al.*, 2022) but little attention has been given to automatic estimation of BW in growing heifers. In the current study, quadratic regressions were formed between BW and the body measurements by including all body measurements with a correlation ≤0.75. This generated a high R^2 value (0.81). Similar studies have not been done on growing heifers and thus this could be useful a reference for future work. However, when combining this data with the image data, the model performance was not improved and in addition, the deep learning model trained using only the Point cloud image data did not give satisfying results ($R^2 = 0.53$). One of the findings from the output of the image acquisition was that the placement of the camera is crucial for a sufficient and correct image capturing. Estimating BW of dairy cows, Anglart (2010) placed a camera high enough to cover the full body length of a fullgrown dairy cow, which according to the author could be a limitation since not all farm buildings have sufficient height ceiling. The aim with mounting a camera high was to be able to capture a full body image of each animal. The camera placement in the current study (240 cm) made it harder to identify the hooks and pin bones for the youngest heifers, as they do not have as fully developed and prominent extremnitys as for older animals. Thus, this contributes with important knowledge on the placement of the camera and requirements for future application to work for growing animals of different body sizes. Changing light conditions and fur colours have previously been reported to be a cause of error (Kuzuhara *et al.*, 2015; Le Cozler *et al*., 2019a) as well as challenges with white and black marks on the animal body (Anglart, 2010; Martins *et al.*, 2020). This was however, not a problem in the current study which may be due to the technical development of hardware.

The choice of top view positiong of the camera was done in accordance with previous studies that have showed better prediction results with top view compared with side view (Martins *et al.*, 2020). The top view position of the camera is also noninvasive and does not interfere with the daily farm operations as side view position can do. If the model in the current study can be trained to extract body measurements from the point cloud images this could improve the model.

6. Conclusions

The main findings in the evaluation of the 3D imaging technique showed that the camera placement need to be adjusted in order to better intentify the body features of heifers of different sizes and ages. However, the high R^2 for manual body measurements and BW indicate that investing the possibility of extracting body features from the images could improve the model performance. The accuracy of the automated BW prediction can be further refined by extracting the body measurements from the Point cloud images. The results also showed that CH had the highest correlation to BW followed by the width between the hip joints measured by the hipometer, thus the CH tape and the hipometer are the most accurate tools in estimating BW in daiy heifers. The hipin measurement has not been described before, and it showed a considerably high correlation to BW which could be used in the future for the automatic feature extraction together with the 3D imaging technology. This could be used for future trials where 3D technology is in use and would help to automate the estimation of BW even further resulting in improvements for monitoring of growth and development of dairy heifers. We conclude that new tools for monitoring growth and development in dairy heifers are needed and this work provides new insight into how this can be achieved.

6.1 Future work

To improve the model estimating BW, it is important to investigate possibility of extracting body measurements automatically from the Point cloud images, instead of using the manual body measurements as input data. In the current study, all manual body measurements (correlation ≤ 0.75) were included in the model training. In order to investigate which body measurements are the most important predicting BW using modeling, feature engineering could be used to narrow down the number of features to the model input. Furthermore, placement of the camera needs to be further investigated to get the best possible images of heifers in different age and weight categories.

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Populärvetenskaplig sammanfattning

Mjölkproduktionen är en viktig del av livsmedelsförsörjningen i stora delar av världen. För att en mjölkko ska kunna producera mjölk behöver det födas en kalv. Kvigkalvarna är framtidens mjölkkor och deras hälsa är grundläggande för att få produktiva, friska och hållbara mjölkkor i framtiden. För att säkerställa tillgången på framtida mjölkkor är en vanlig strategi att mjölkbönder föder upp sina egna kvigkalvar tills de är redo att börja producera mjölk. Ur ett ekonomiskt perspektiv är en vanlig rekommendation att kvigan ska kalva första gången mellan 22-24 månaders ålder. Om kvigan är för liten (storlek/kroppsvikt) eller för gammal (över 3 år) vid första kalvningen ökar risken för kalvningssvårigheter. Storleken och kroppsvikten är avgörande för när kvigan blir könsmogen vilket även påverkar när hon kan producera sin första kalv. För att minimera risken för kalvningssvårigheter vid första kalvningen är det däför viktigt med en tillräcklig tillväxt hos kvigorna under uppfödningsperioden och en kännedom om kvigornas kroppsvikt.

Tillväxten kan variera under olika perioder av kvigans uppväxt och det är därför viktigt med regelbunden uppföljning. Den vanligaste metoden är att väga kvigorna, men det går även att mäta olika kroppsmått för att få reda på kvigans vikt genom skattning. De flesta mätningar som kan användas för att registrera tillväxten är dock väldigt arbetskrävande, tidskrävande och kan orsaka höga stressnivåer hos kvigorna. Forskning har undersökt möjligheten att med hjälp av tredimensionell bildteknik automatisera viktskattningen hos mjölkkor. Däremot är liknande forskning för växande kalvar och kvigor otillräcklig vilket lämnar osäkerheter om i vilken utsträckning tredimensionell bildteknik kan användas till kvigor.

I det här examensarbetet genomfördes en studie med syfte att utvärdera tredimensionell (3D) bildteknik genom användning av en 3D kamera, för att uppskatta kroppsvikt och tillväxt hos mjölkraskvigor. För att kunna utvärdera syftet samlades kroppsviker, tredimensionella bilder och nio olika kroppsmått in. Kroppsmåtten samlades in med fyra olika mätverktyg. Det var även viktigt att förstå vilka kroppsmått som är högst korrelerade till kroppsvikten och vilka mätverktyg som uppskattar kroppsvikten bäst.

Utvärdering av 3D kameran visade att placeringen av kameran behöver justeras för att bättre identifiera de viktiga kroppsdelar hos kvigor i olika storlek och ålder. Resultaten visar även på möjligheten att extrahera kroppsegenskaper direkt från bilderna för att i framtiden automatisera uppskattningen av kroppsvikt ytterligare vilket skulle resultera i förbättringar för övervakning av tillväxt och utveckling av mjölkraskvigor. Resultaten visade högst korrelationer mellan kroppsvikt och viktbandet som användes för att mäta bröstomfånget, vilket överensstämmer med tidigare forskning. I framtiden behöver en undersökning ske för att veta vilka kroppsmått som ska användas. Det kan också vara intressant att undersöka vid vilken ålder det är viktigast att ha en stabil tillväxttakt ur ett avelsperspektiv.

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Appendix

Figure 9. Picture of the entrence (left) and the exit (right) from the electronic weighing scale.

Figure 10. Pictures of the hipometer (left) and the height stick (right) when used in the barn.

Table 8. Information about the number of animals each collection, the number of animals that got body measurements taken, breed, age and body weight.

Data collection	Nr of animals	Nr of animals - measurements[1]	SRB (%)	SH (%)	Age (mo)	BW (kg)
1	136	89	54	46	6-15	205-561
2	140	109	59	41	6-19	222-575
3	134	108	57	43	7-18	202-549
4	123	92	56	44	6-19	174-555
5	121	94	58	42	6-19	190-558
6	124	66	57	43	7-19	191-570

[1] CG, BL, HW, BaW, IW, Hipin, HH, WH and width between the hip joints at the point of the grater trochanters

Table 9. Descriptive statistics of the collected variables.

Variable	**Mean**	**Min**	**Max**
BW (kg)	357.5	174.0	575.0
CG (kg)	331.0	175.0	569.0
Hipometer (kg)	331.8	170.0	552.0
CG (cm)	159.7	127.0	196.0
BL (cm)	117.5	88.00	152.0
HW (cm)	42.43	30.00	57.00
BaW (cm)	57.64	40.00	74.00
IW (cm)	17.52	12.00	26.00
Hipin (cm)	48.23	34.00	62.00
WH (cm)	122.9	103.0	143.0
HH (cm)	130.4	107.0	150.0

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