

Article

Accuracy of Thoracic Tape-Based Live-Weight Estimation in Minhota Calves: Effects of Age, Sex and Dam Parity

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Simple Summary

Knowing the live weight of calves is important for good farm management, but many farms do not have easy access to weighing scales. Measuring tapes that estimate weight from the chest circumference of an animal are cheaper and easier to use, but their accuracy needs to be checked before farmers rely on them. This study tested whether a thoracic measuring tape could accurately estimate the live weight of Minhota calves, a Portuguese cattle breed used mainly for meat production. The tape estimates were compared with weights obtained using a scale, using 210 records from 68 calves. Overall, the tape followed the scale weights very closely and had an average error of about 5%, showing that it can be useful for routine monitoring of calf growth. However, the tape was not equally accurate at all ages. It was closer to the scale in younger calves in terms of kilogram error, but it increasingly underestimated the weight of older and heavier calves. Sex and dam parity had little effect. These findings are useful because they support the use of a simple, low-cost tool for farm monitoring, while showing that scales remain preferable when exact weight is needed.

Abstract

Accurate live-weight monitoring is important for calf management, but calibrated scales are not always available under farm conditions. This study evaluated the accuracy of a thoracic measuring tape for estimating live weight in Minhota calves and examined whether tape error was influenced by age, sex and dam parity. The dataset included 210 repeated weighing records from 68 biologically distinct calves. Scale-measured live weight was used as the reference value, and tape accuracy was assessed using signed error, absolute error, percentage error, absolute percentage error, correlation and Bland–Altman analysis. Repeated-measures regression models were used to account for multiple records from the same calf. Tape-estimated live weight was very strongly correlated with scale-measured live weight ($r = 0.997$). The tape showed a small average underestimation of live weight, with a mean signed error of -3.02 kg, mean absolute error of 7.79 kg, root mean squared error of 11.92 kg and mean absolute percentage error of 4.97% . Age was the main factor associated with tape accuracy. For every additional 100 days of age, signed error decreased by 5.74 kg, indicating increasing underestimation in older calves. Sex and dam parity had limited effects. The thoracic measuring tape is a useful practical tool for routine monitoring of Minhota calf growth, but age-related bias should be considered, especially in older and heavier calves.



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1. Introduction

Accurate monitoring of live weight is an important component of animal management, particularly during early life, when growth performance reflects nutrition, health status and adaptation to the production system. In calves, repeated weight records can support decisions related to feeding, health monitoring, treatment dosage, growth evaluation and marketing. Monitoring body weight and average daily gain from early life has been recommended to support farm-level decisions and improve later performance, including reproductive efficiency in heifers [1]. Early life nutrition has also been shown to influence calf growth, inflammatory status and health indicators, reinforcing the importance of weight monitoring as part of calf management [2]. Accurate body-weight information is also relevant for veterinary treatments, because several cattle medications are dosed according to mg/kg body weight [3]. In beef systems, live weight and calf weaning weight are central components of productive and economic efficiency, with calf weaning weight contributing substantially to annual liveweight production [4].

The most accurate method for determining live weight is the use of calibrated livestock scales. However, access to scales is not always practical under commercial farm conditions. Weighing facilities may be expensive, time-consuming to use, difficult to transport and stressful for animals when repeated handling is required [5,6]. These limitations are particularly relevant in small- and medium-scale farms, extensive or semi-extensive systems and local-breed production systems, where animals may be managed in dispersed holdings and where routine weighing infrastructure may be limited. For these reasons, indirect methods of estimating live weight remain widely used in cattle production, particularly those based on thoracic perimeter or heart-girth measurements [5,7,8].

Among indirect methods, thoracic perimeter, also referred to as heart girth, is one of the most common body measurements used to estimate live weight in cattle. The biological basis of this approach is that thoracic circumference is strongly associated with body size, skeletal development and body mass. Measuring tapes are inexpensive, portable, easy to use and require minimal equipment, making them useful tools for on-farm monitoring. Previous studies have shown strong associations between heart girth and body weight in cattle, including calves and growing animals [5–8]. Nevertheless, strong correlation does not necessarily imply full agreement between methods. A tape may rank animals correctly but still systematically overestimate or underestimate live weight.

The accuracy of tape-based weight estimation may be influenced by several factors. Age and body size are particularly important because the relationship between thoracic perimeter and live weight may change as calves grow; recent work in pre-weaned Holstein–Friesian calves showed that morphometric prediction of body weight depends on age-specific calf development and that heart girth is a key predictor of body weight [8]. In young calves, thoracic development, body proportions and tissue composition may differ from those of older animals, potentially affecting the validity of tape equations [5,8]. Sex may also contribute to variation in growth and body conformation, with male and female calves differing in body size and development patterns; for example, calf birth-weight studies have reported sex-related differences in body weight, with male calves generally heavier than females [9]. In addition, dam parity may influence early calf growth because calves born from primiparous and multiparous dams may differ in birth weight, maternal environment and early life performance. Duncan et al. [10] reported lower birth weight in

calves born to primiparous dams than in calves born to multiparous dams, while Condon et al. [9] also identified parity as one of the cow-level factors associated with calf birth weight. These factors could affect not only true live weight, but also the relationship between body dimensions and weight estimated from a tape.

Validation of tape-based weight estimation therefore requires more than simple correlation analysis. Correlation measures the strength of association between two methods, but it does not demonstrate that both methods give numerically similar values or that one method can replace the other [11,12]. Agreement-based approaches are therefore needed to assess both the magnitude and direction of error. Signed error can identify systematic bias, while absolute error and absolute percentage error quantify the practical magnitude of disagreement between estimated and observed values [13,14]. Bland–Altman analysis is also useful because it evaluates agreement across the measurement range and can reveal proportional bias, where error changes as animals become heavier [11,12,15]. When repeated records are available from the same animals, statistical models should also account for within-animal dependence rather than treating all observations as independent [16,17].

The Minhota is a Portuguese autochthonous cattle breed traditionally associated with the north-western region of Portugal, particularly the former Minho region and the district of Viana do Castelo [18,19]. Historically, the breed was valued for triple-purpose use, including meat, milk and draught work; however, milk production and draught use are now residual, and current production is mainly oriented towards meat [19]. The principal commercial product is veal, with animals commonly sold for slaughter at approximately 6.2 months of age, and more than half of Minhota slaughtered animals classified as veal carcasses [19]. In such local-breed systems, simple and reliable tools for monitoring calf growth may be especially valuable, provided that their accuracy is properly assessed under the specific production and animal conditions in which they are used [5,8].

This study aimed to evaluate the accuracy of a thoracic measuring tape for estimating live weight in Minhota calves. Specifically, tape-estimated live weight was compared with scale-measured live weight, and tape accuracy was assessed using signed error, absolute error, percentage error and absolute percentage error. The study also examined whether tape accuracy was influenced by calf age, sex and dam parity. We hypothesised that tape-estimated live weight would be strongly associated with scale-measured live weight, but that the magnitude and direction of tape error would vary with calf age and, to a lesser extent, with sex and dam parity.

2. Materials and Methods

2.1. The Animals and Dataset

The dataset consisted of repeated live-weight records from Minhota calves. Each record included calf identification, calf name, sex, date of birth, date of weighing, age at weighing, scale-measured live weight, thoracic perimeter measured using a tape, tape-estimated live weight, dam identification and dam parity class. Calf sex was coded as female or male. Dam parity was classified as multiparous or primiparous.

Thoracic perimeter was measured using a commercial heart-girth measuring tape/weigh-band (Wiegband farmer's boy, Dalton Supplies, Ltd., Nettlebed, UK). The tape provided two readings: thoracic perimeter and the corresponding live-weight estimate. In this study, "tape-estimated live weight" refers to the live-weight value read directly from the measuring tape at the time of measurement. It was not calculated by the authors from a newly fitted prediction equation. The calibration population and equation used by the manufacturer to convert thoracic perimeter into estimated live weight were not available; therefore, the present study should be interpreted as a field validation of the tape-provided live-weight estimate in Minhota calves.

In the present study, “tape-estimated live weight” refers to the live-weight value read directly from the thoracic measuring tape after measuring the calf’s thoracic perimeter. Thus, this variable represents the weight estimate provided by the measuring tape/weigh-band itself. It was not calculated by the authors from a newly developed prediction equation. The thoracic perimeter was recorded separately, allowing the relationship between perimeter and tape-estimated weight to be described, but the validation analysis used the tape-provided live-weight estimate as the method under evaluation and scale-measured live weight as the reference value.

Live weight was measured using a livestock scale and was considered the reference value. The scale used was a Báscula Cabral, model 23 (António Antunes & Filho, Lda, Braga, Portugal) with a readability of 100 g.

Thoracic perimeter was measured with the calf standing in a normal quadrupedal position. The measuring tape was placed around the thorax immediately behind the forelimbs, at the level of the heart girth, and maintained in contact with the hair coat without intentional compression of the soft tissues. The tape-estimated live weight was read directly from the weight scale printed on the measuring tape/weigh-band. For each weighing event, one scale weight and one tape reading were recorded. Scale and tape measurements were obtained sequentially during the same handling session on the same day. The readings were not recorded blind to one another, because the same operator had access to both measurements during the weighing event. For each weighing event, one scale weight and one tape reading were recorded; therefore, the dataset did not include repeated tape readings or independent duplicate measurements.

The final dataset included 210 weighing records from 68 biologically distinct calves. Calf identity was checked using both SIA and calf name because one SIA value was duplicated for two different calves. Therefore, the number of unique calves reported in the descriptive subgroup summaries was based on biologically distinct calf records rather than on SIA alone. Because several calves were measured more than once, calf identity was accounted for in the statistical modelling to address repeated observations. Data were collected at the School of Agriculture of the Polytechnic University of Viana do Castelo. It is open access and is available at <http://doi.org/10.13140/RG.2.2.25750.51524> [20].

The relationship between thoracic perimeter and tape-estimated live weight provided by the measuring tape is shown descriptively in Appendix A.

2.2. Definition of Tape Accuracy Variables

Scale-measured live weight was considered the reference value. Tape accuracy was evaluated by comparing the live-weight estimate read directly from the thoracic measuring tape with the corresponding scale-measured live weight recorded at the same weighing event. Therefore, the study assessed the agreement between the tape-provided weight estimate and the scale weight, rather than developing a new equation from thoracic perimeter. The live-weight estimate was read directly from the weight scale printed on the tape after the thoracic perimeter was measured. The following variables were calculated for each weighing record:

Signed error (SiE) was calculated as

$$\text{Signed error} = \text{tape-estimated live weight} - \text{scale-measured live weight} \quad (1)$$

Negative values indicate that the tape underestimated live weight, whereas positive values indicate that the tape overestimated live weight.

Absolute error (AE) was calculated as the absolute difference between tape-estimated and scale-measured live weight. Percentage error (PE) was calculated as

$$\text{Percentage error} = \frac{\text{tape} - \text{estimated live weight} - \text{scale} - \text{measured live weight}}{\text{scale} - \text{measured live weight}} \times 100 \quad (2)$$

Absolute percentage error (APE) was calculated as the absolute value of percentage error. These complementary indicators were used to assess both systematic bias and practical accuracy.

2.3. Descriptive and Agreement Analyses

Descriptive statistics were calculated for age, scale-measured live weight, tape-estimated live weight, thoracic perimeter, SiE, AE, PE and APE. Results are presented as mean, standard deviation, median, minimum and maximum.

Agreement between scale-measured and tape-estimated live weight was assessed using Pearson's correlation, mean signed error (MSIE), root mean squared error (RMSE), mean absolute error (MAE) and mean absolute percentage error (MAPE). A Bland–Altman analysis was adapted to the repeated-measures structure of the dataset. Mean bias was estimated using a model for signed error that included calf identity as a random effect. The limits of agreement were calculated as the estimated mean bias $\pm$ 1.96 times the square root of the combined between-calf and within-calf variance components. This approach was used to avoid treating repeated records from the same calf as independent observations. The mean of scale and tape weight was plotted against signed error to assess whether tape error changed with increasing body weight.

2.4. Statistical Modelling

The effect of calf age, sex and dam parity on tape accuracy was analysed using repeated-measures regression models. As calves contributed unequal numbers of records, generalised estimating equations (GEEs) were used with calf identity as the clustering variable. An exchangeable working correlation structure and robust standard errors were used.

Three dependent variables were analysed separately: signed error (SiE), to evaluate systematic bias; absolute error (AE), to evaluate magnitude of error in kg; and absolute percentage error (APE), to evaluate relative error. The main GEE models were fitted using a Gaussian working distribution with an identity link. This specification was considered appropriate for SiE because signed error can take both negative and positive values and was analysed on the original kg scale. For AE and APE, which are non-negative and right-skewed, the Gaussian identity-link models were used as marginal models to estimate mean differences in error magnitude on the original scale, with inference based on robust sandwich standard errors. Model outputs for AE and APE were therefore interpreted as average differences in error magnitude rather than as fully distributional models of bounded outcomes.

The fixed explanatory variables were calf age, sex and dam parity. Age was modelled as a continuous variable and expressed per 100 days to facilitate interpretation. Female calves and calves from multiparous dams were used as reference categories. Statistical significance was assessed at $p < 0.05$.

Because AE and APE are bounded at zero and showed right-skewed distributions, a sensitivity analysis was also performed using log-transformed AE and log-transformed APE, with a small constant added to retain observations with zero error. These sensitivity models used the same explanatory variables and calf identity as the clustering variable. The direction and interpretation of the main findings were compared with those from the original-scale GEE models.

Data handling, descriptive statistics, calculation of accuracy indicators and graphical outputs were performed using Python 3.13.5. Descriptive statistics and accuracy indicators, including SiE, AE, PE, APE, MAE, and RMSE, were calculated using pandas 3.0.5 and

NumPy 2.3.5. Correlation, agreement analyses, and the repeated-measures Bland–Altman values were performed and calculated using SciPy 1.17.0 and statsmodels 0.14.6. Graphical outputs, including scatterplots, Bland–Altman plots and boxplots, were produced using Matplotlib 3.10.8.

The repeated-measures regression models were fitted separately using the GEE routine in IBM Corp.[®] SPSS[®] Statistics, Armonk, NY, USA, version: 29.0.2.0 (20), where calf identity was included as the clustering variable.

3. Results

Tape accuracy was assessed by comparing the live-weight value read directly from the thoracic measuring tape with scale-measured live weight. The results are presented in four parts: descriptive characteristics of the dataset; overall agreement between scale-measured and tape-estimated live weight; tape accuracy according to calf age, sex and dam parity; and repeated-measures models testing whether age, sex and dam parity influenced tape accuracy after accounting for repeated measurements from the same calves.

3.1. Descriptive Characteristics of the Dataset

The dataset included 210 weighing records from 68 calves. The descriptive characteristics of calf age, scale-measured live weight, tape-estimated live weight, thoracic perimeter and tape accuracy variables are presented in Table 1. Calves covered a wide range of ages and body weights, with age ranging from birth to 344 days. Mean scale-measured live weight was 179.7 kg, while mean tape-estimated live weight was slightly lower, at 176.7 kg. The MSIE was -3.0 kg, indicating a small average underestimation of live weight by the measuring tape.

Table 1. Descriptive statistics for calf age, live weight, thoracic perimeter and tape accuracy variables.

Variable	Mean	SD	Median	Minimum	Maximum
Age, days	114.00	97.91	90.50	0.00	344.00
Scale-measured live weight, kg	179.71	123.79	145.00	34.85	530.00
Tape-estimated live weight, kg	176.70	117.73	144.50	39.00	525.00
Thoracic perimeter	120.27	32.15	118.50	69.00	187.00
Signed error, kg	-3.02	11.56	0.50	-55.00	15.00
Absolute error, kg	7.79	9.04	4.32	0.00	55.00
Percentage error, %	0.96	6.33	0.77	-15.94	20.45
Absolute percentage error, %	4.97	4.03	4.02	0.00	20.45

Note: Values describe the full dataset of repeated weighing records. Signed error was calculated as tape-estimated live weight minus scale-measured live weight. Negative values indicate underestimation by the measuring tape. $N = 210$.

The negative MSIE shows that, overall, the measuring tape slightly underestimated scale-measured live weight. However, the median SiE was close to zero, indicating that the average bias was influenced by larger underestimations in some records. The MAE was 7.8 kg, while the MAPE was approximately 5%, suggesting good practical accuracy overall. The negative mean signed error and the positive mean percentage error are not contradictory, because percentage error expresses each kg difference relative to the calf's body weight; therefore, small overestimations in lighter calves can have a greater influence on the average percentage error than similar kg differences in heavier calves.

3.2. Overall Agreement Between Scale-Measured and Tape-Estimated Live Weight

The overall relationship between scale-measured and tape-estimated live weight was first examined graphically. Figure 1 compares the two methods directly, with the identity

line representing perfect agreement. This figure shows whether tape-estimated weights followed the same pattern as scale-measured weights across the full weight range.

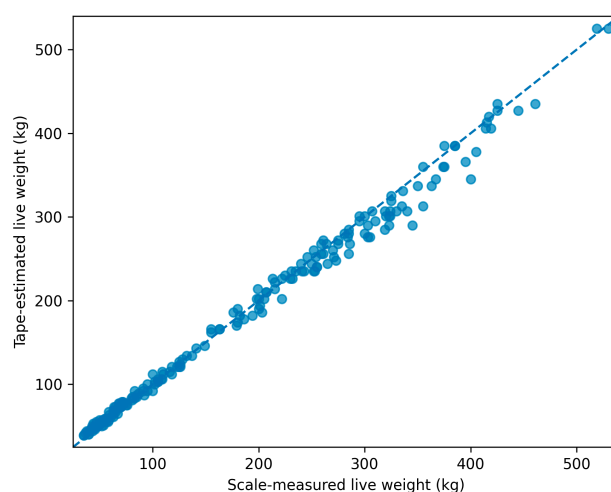


Figure 1. Relationship between scale-measured and tape-estimated live weight in Minhota calves. Each point represents one weighing record. The dashed identity line represents perfect agreement between scale-measured and tape-estimated live weight. Points close to the line indicate close agreement between the two methods.

Tape-estimated live weight was strongly associated with scale-measured live weight. Most observations were located close to the identity line, indicating that the measuring tape closely followed variation in calf LW. Nevertheless, visual inspection also showed that the tape estimates were not identical to scale weights, particularly at higher body weights.

To complement the visual assessment, agreement between scale-measured and tape-estimated live weight (LW) was quantified using correlation and error-based statistics. These statistics are presented in Table 2. Correlation was used to evaluate the strength of association between methods, while MSIE, MAE, root mean squared error (RMSE) and MAPE were used to describe bias and practical prediction error.

Table 2. Agreement between live weight measured by scales and estimated using a tape.

Statistic	Estimate	Interpretation
Pearson's correlation	0.997	Very strong association between methods
Mean signed error	−3.02 kg	Average underestimation by the tape
Repeated measures mean bias	−2.76 kg	Model-based bias accounting for repeated records
95% CI for repeated measures mean bias	−4.57 to −0.95 kg	Mean bias significantly below zero
Repeated measures limits of agreement	−25.38 to 19.87 kg	Individual tape estimates may vary substantially
Mean absolute error	7.79 kg	Average absolute deviation from scale weight
Root mean squared error	11.92 kg	Penalises larger errors
Mean absolute percentage error	4.97%	Average relative error

Note: Agreement was assessed using correlation, mean signed error, repeated measures confidence interval for mean signed error, repeated measures limits of agreement, mean absolute error, root mean squared error and mean absolute percentage error.

The Pearson correlation coefficient between scale-measured and tape-estimated LW was 0.997, confirming a very strong association between the two methods. However, the tape showed a small negative MSIE of −3.02 kg, indicating slight underestimation of LW. When the repeated-measures structure was accounted for, the model-based Bland–Altman mean bias was −2.76 kg, with a 95% confidence interval from −4.57 to −0.95 kg. The repeated-measures limits of agreement ranged from −25.38 to 19.87 kg, indicating that individual tape estimates could still differ substantially from scale-measured values. The

MAE was 7.79 kg, the root mean squared error was 11.92 kg, and the MAPE was 4.97%, showing good average practical accuracy but non-negligible individual-level error.

Agreement between the two methods was further explored using a Bland–Altman plot. Figure 2 shows the signed difference between tape-estimated and scale-measured LW across the range of mean body weights. The plotted bias and limits of agreement correspond to the repeated-measures Bland–Altman estimates, with calf identity accounted for in the estimation of the mean bias and variance components.

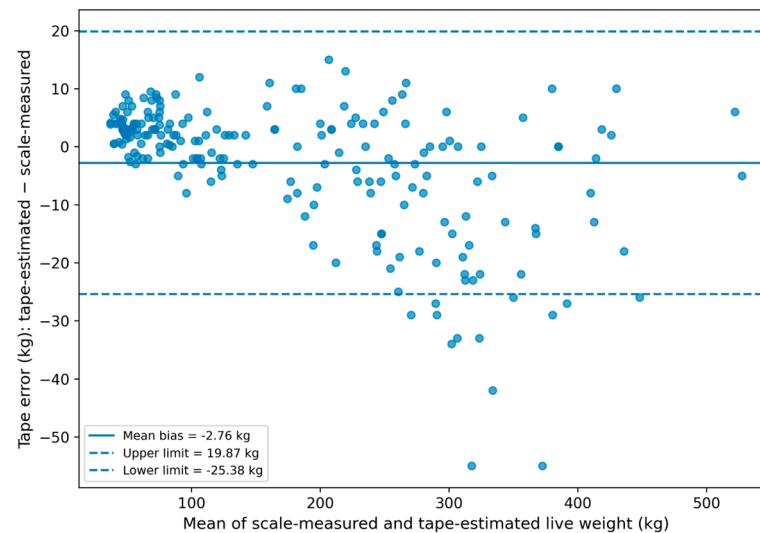


Figure 2. Bland–Altman plot comparing tape-estimated and scale-measured live weight. The x-axis represents the mean of tape-estimated and scale-measured live weight, and the y-axis represents signed error, calculated as tape-estimated minus scale-measured live weight. The central horizontal line represents the repeated measures mean bias, and the outer dashed lines represent the repeated measures limits of agreement.

The Bland–Altman analysis showed a small negative mean bias, consistent with slight underestimation by the tape method. The repeated-measures limits of agreement ranged from -25.38 to 19.87 kg, indicating that individual tape estimates could differ substantially from scale-measured weights. The distribution of points also suggested proportional bias, with tape estimates becoming increasingly lower than scale-measured weights in heavier calves.

3.3. Tape Accuracy According to Age, Sex and Dam Parity

Tape accuracy was then examined according to calf age class, sex and dam parity. These descriptive comparisons are presented in Table 3. This table was included to identify whether error patterns differed between biologically relevant groups before testing these effects in repeated-measures models.

The clearest descriptive pattern was observed for calf age. In calves aged 0–90 days, the tape slightly overestimated LW, with a MSIE of 2.39 kg. In contrast, the tape underestimated LW in older calves. The MSIE was -4.24 kg in calves aged 91–180 days, -10.23 kg in calves aged 181–270 days and -14.00 kg in calves older than 270 days.

To make this age-class pattern easier to visualise, signed tape error was plotted by age class in Figure 3. This figure shows the direction and spread of tape error within each age group and illustrates how the tape changed from slight overestimation in young calves to underestimation in older calves.

Table 3. Tape accuracy according to sex, dam parity and age class.

Group	n	Calves	MA (Days)	SW (kg)	TW (kg)	SiE (kg)	AE (kg)	APE (%)	RMSE (kg)
Female	92	33	115.61	171.78	169.76	−2.02	6.68	4.59	10.16
Male	118	35	112.75	185.90	182.10	−3.80	8.66	5.27	13.13
Multiparous dam	177	58	114.20	182.64	179.02	−3.62	8.24	5.05	12.62
Primiparous dam	33	10	112.91	164.02	164.24	0.22	5.38	4.55	7.04
0–90 days	105	61	26.69	73.97	76.35	2.39	3.80	5.91	4.60
91–180 days	38	27	143.08	207.53	203.29	−4.24	8.82	4.00	11.31
181–270 days	57	41	219.63	319.33	309.11	−10.23	13.28	4.09	18.43
>270 days	10	8	318.20	388.50	374.50	−14.00	14.60	3.77	18.43

Note: Values are presented by group to describe variation in tape accuracy according to biological and management-related factors. Signed error indicates direction of bias, whereas absolute error and absolute percentage error describe the magnitude of the error. MA—mean age; SW—scale weight; TW—tape weight; SiE—signed error; AE—absolute error; APE—absolute percentage error; RMSE—root mean squared error.

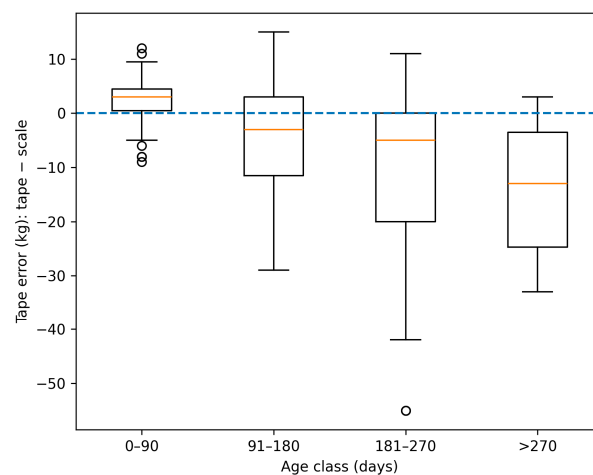


Figure 3. Grouped box-and-whisker plot showing the distribution of tape-estimation error within each age class. Signed tape error according to calf age class. Values represent the distribution of signed error within each age class. The measuring tape slightly overestimated live weight in the youngest calves but increasingly underestimated live weight in older calves. Orange line: median error; Box: interquartile range, from the 25th to the 75th percentile; Whiskers: values within the standard whisker limits, usually $1.5 \times \text{IQR}$; Circles: potential outliers; Blue dashed line at 0 kg: perfect agreement between methods.

The age-class plot confirms that tape accuracy was not constant across calf age. The tape was closest to the scale-measured value in younger calves, whereas underestimation became progressively more evident in older age groups. Because age was also available as a continuous variable, the association between calf age and signed tape error was examined more directly. Figure 4 presents SE across the full age range of the dataset. This figure was used to assess whether the age-related change in tape error followed a continuous trend rather than only differences between age categories.

The continuous-age plot confirmed that increasing age was associated with progressively more negative tape error. This indicates that the measuring tape became increasingly likely to underestimate LW as calves aged. Sex-related differences in tape accuracy were also examined. Female calves had a MSIE of −2.02 kg, whereas male calves had a MSIE of −3.80 kg. AE and APE were also numerically higher in males. Figure 5 presents the distribution of APE by sex, allowing comparison of relative tape accuracy between female

and male calves. The figure shows that the distributions of APE were broadly similar between sexes. Although males showed slightly higher numerical error, the difference was small compared with the effect observed for age.

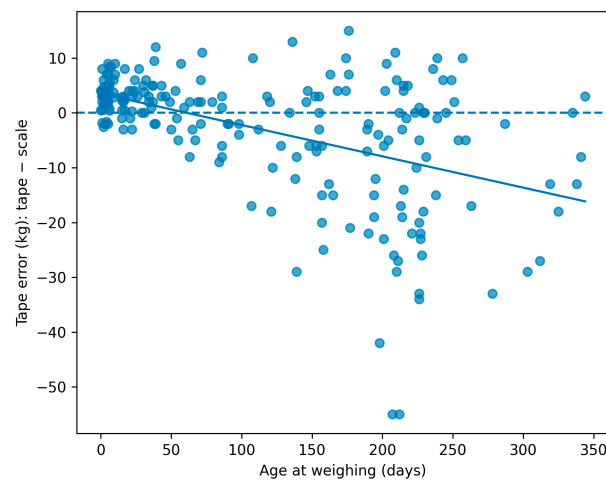


Figure 4. Association between calf age and signed tape error. Signed error was calculated as tape-estimated live weight minus scale-measured live weight. Negative values indicate underestimation by the measuring tape, whereas positive values indicate overestimation. The fitted line shows the trend in tape error with increasing calf age. Blue dots: individual weighing observations; Blue dashed horizontal line at 0 kg: perfect agreement between the two methods; Solid blue line: fitted linear regression.

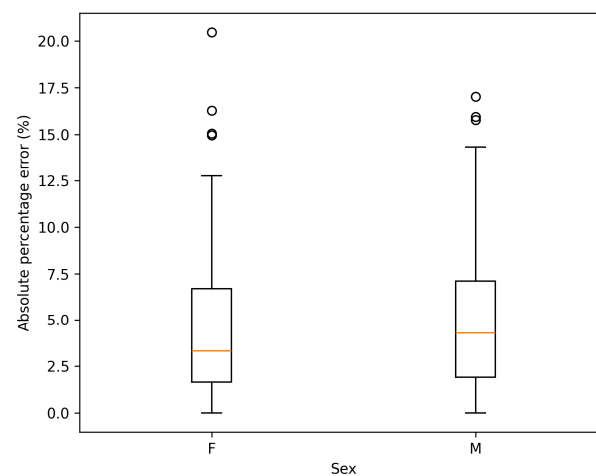


Figure 5. Absolute percentage error of tape-estimated LW according to calf sex. Absolute percentage error was calculated as the absolute difference between tape-estimated and scale-measured live weight divided by scale-measured live weight and multiplied by 100. The figure compares the relative accuracy of the measuring tape between female and male calves. F—female, M—male. Boxes represent the interquartile range, orange lines indicate medians, whiskers extend to observations within 1.5 times the interquartile range, and open circles represent potential outliers.

Dam parity was also evaluated as a possible source of variation in tape accuracy. Calves from multiparous dams had a MSIE of -3.62 kg, whereas calves from primiparous dams had a MSIE of 0.22 kg. Figure 6 presents the distribution of APE according to dam parity class and provides a visual comparison of relative tape accuracy between calves from multiparous and primiparous dams.

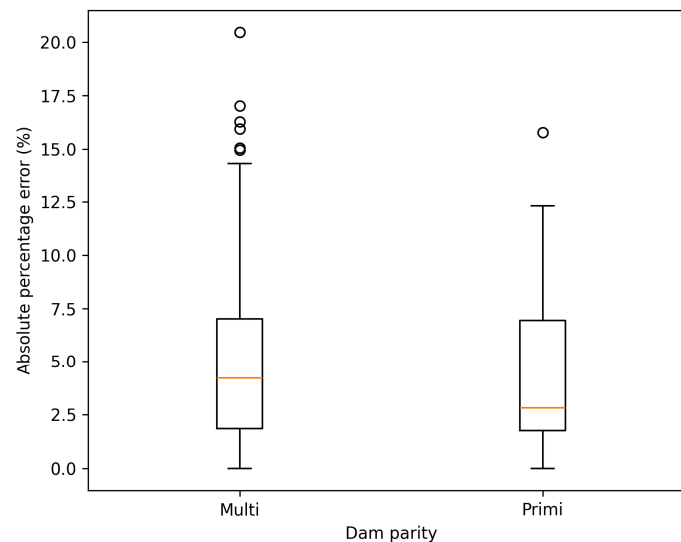


Figure 6. Absolute percentage error of tape-estimated live weight according to dam parity class. Absolute percentage error was compared between calves born from multiparous (Multi) and primiparous (Primi) dams. The figure illustrates the relative accuracy of the tape method according to dam parity. Boxes represent the interquartile range, orange lines indicate medians, whiskers extend to observations within 1.5 times the interquartile range, and open circles represent potential outliers.

The distribution of relative error was broadly similar between parity classes. Although calves from multiparous dams showed greater average underestimation, the primiparous group included fewer records, so this comparison should be interpreted cautiously.

Altogether, the descriptive analyses showed that calf age was the factor most clearly associated with tape error. Differences according to sex and dam parity were smaller and less consistent.

3.4. Repeated-Measures Regression Models

Repeated-measures models were used to test whether age, sex and dam parity were associated with tape accuracy while accounting for multiple records from the same calf. Separate models were fitted for signed error, AE and APE. The model results are shown in Table 4. This table provides the formal statistical test of whether each explanatory variable influenced tape bias or error magnitude.

Age was the main predictor of tape accuracy. For signed error, age had a negative effect: for every additional 100 days of age, tape error decreased by 5.74 kg. This means that the tape estimate became progressively lower than the scale-measured weight as calves aged. This result is consistent with the age-related patterns shown graphically in Figures 3 and 4.

For AE, age also had a significant effect. Each additional 100 days of age increased the absolute difference between tape-estimated and scale-measured LW by 4.16 kg. This shows that the practical error in kg increased as calves became older. However, for APE, age had a negative effect, indicating that although the absolute difference in kg increased with age, the relative error represented a slightly smaller proportion of body weight in older calves.

Sex was not significantly associated with signed error, AE or APE after accounting for age and dam parity. Male calves had numerically larger errors than female calves, but these differences were not statistically significant.

Table 4. Repeated-measures models evaluating the effect of age, sex and dam parity on tape accuracy.

Outcome	Predictor	β	SE	95% CI	<i>p</i> -Value
Signed error (kg)	Intercept	4.28	1.07	2.18; 6.38	<0.001
	Age, per 100 days	−5.78	0.85	−7.45; −4.1	<0.001
	Male vs. female	−1.87	1.60	−5.01; 1.27	0.243
	Primiparous vs. multiparous dam	3.73	1.64	−0.51; 6.95	0.023
Absolute error (kg)	Intercept	2.31	0.74	0.87; 3.76	0.002
	Age, per 100 days	4.16	0.70	2.79; 5.53	<0.001
	Male vs. female	1.91	1.17	−0.40; 4.21	0.105
	Primiparous vs. multiparous dam	−2.81	1.34	−5.44; −0.18	0.036
Absolute percentage error (%)	Intercept	5.97	0.64	4.72; 7.22	<0.001
	Age, per 100 days	−1.12	0.31	−1.73; −0.51	<0.001
	Male vs. female	0.65	0.56	−0.45; 1.75	0.246
	Primiparous vs. multiparous dam	−0.55	0.61	−1.74; 0.63	0.361

Note: Models accounted for repeated observations from the same calf, with calf identity defined using biologically distinct calf records. Age was expressed per 100 days. Female calves and calves from multiparous dams were used as reference categories. GEE models used a Gaussian working distribution with identity link and robust standard errors. For absolute error and absolute percentage error, results represent marginal mean differences in error magnitude on the original scale. Sensitivity analyses using log-transformed absolute error and absolute percentage error led to the same substantive conclusions.

Dam parity was associated with signed error and absolute error after correction of the calf identity variable. Calves from primiparous dams showed less underestimation than calves from multiparous dams, with signed error higher by 3.73 kg. They also showed lower absolute error, by 2.81 kg. However, dam parity was not significantly associated with absolute percentage error. Because the primiparous group included relatively few calves, this result should be interpreted cautiously.

Because AE and APE are non-negative error-magnitude outcomes, sensitivity analyses were performed using log-transformed AE and log-transformed APE. These models confirmed the main interpretation of the original-scale GEE models. Age remained the dominant factor associated with tape accuracy: increasing age was associated with higher absolute error and lower relative percentage error. Sex and dam parity did not materially change the interpretation of the models for relative error. Therefore, the conclusions were not dependent on modelling AE and APE on the original scale.

Altogether, the measuring tape showed good practical accuracy, with a MAPE of approximately 5%. However, tape accuracy was age-dependent and depended on how error was expressed. In younger calves, bias and absolute error in kg were smaller, whereas older calves showed increasing underestimation and larger absolute error. Conversely, APE was highest in the 0–90 day group, indicating that even small kg errors represented a larger proportion of body weight in lighter calves.

3.5. Main Finding

The measuring tape was highly correlated with scale-measured LW and had an average APE of approximately 5%, indicating good practical accuracy overall. However, tape accuracy was age-dependent and differed according to the error metric considered. In younger calves, the tape showed the smallest bias and absolute error in kg, whereas older and heavier calves showed increasing underestimation and larger absolute error. By contrast, relative error expressed as APE was highest in the youngest age group, because a small kg difference represents a larger proportion of body weight in lighter calves. Sex had

little effect on tape accuracy. Dam parity was associated with signed error and absolute error, with calves from primiparous dams showing less underestimation and lower absolute error, although this finding should be interpreted cautiously because the primiparous group was relatively small.

4. Discussion

This study evaluated the accuracy of a thoracic measuring tape for estimating LW in Minhota calves and examined whether tape error was influenced by calf age, sex and dam parity. The results showed that tape-estimated LW was very strongly associated with scale-measured LW, consistent with previous studies showing that heart-girth or thoracic measurements can provide accurate calf body-weight estimates [5,8]. However, the analysis also showed that high correlation did not imply perfect agreement. This distinction is important because correlation measures association, not interchangeability between methods [11,12]. The tape showed a small average underestimation of LW and, more importantly, the magnitude and direction of error changed with calf age. Therefore, although the tape may be useful for routine on-farm monitoring, its estimates should be interpreted with caution. In older and heavier calves, the main concern is increasing underestimation and larger absolute error in kg, whereas in younger and lighter calves, even smaller kg errors may represent a larger percentage of body weight.

The very high correlation between tape-estimated and scale-measured LW confirms the expected close relationship between thoracic perimeter and body mass. This agrees with previous work showing that heart girth or thoracic circumference is one of the most informative linear body measurements for predicting LW in cattle [5,8,21–23]. From a practical perspective, this is important because measuring tapes are inexpensive, portable and easy to use under farm conditions. They may be particularly useful in farms where weighing scales are unavailable or where frequent weighing is difficult due to labour, handling facilities or animal-management constraints [5,8]. In local-breed or small-scale production systems, such as those involving Minhota calves, this type of simple tool may therefore support growth monitoring and management decisions, provided that the method is validated for the target animal population [5,24].

Nevertheless, the results also highlight the limitations of relying only on correlation to validate a measurement method. Although the Pearson correlation coefficient was very high, the tape did not always reproduce scale-measured LW accurately. This distinction between association and agreement is important because correlation measures the strength of a linear relationship, but does not demonstrate that two methods give numerically similar values or can be used interchangeably [11,12]. The MSIE was -3.02 kg, indicating slight overall underestimation, while the MAE was 7.79 kg and the RMSE was 11.92 kg. These indicators show that the tape performed well on average, but that some individual estimates differed considerably from scale weight. A method can rank animals correctly while still producing biased estimates, especially at particular body weights or ages [12,25]. For this reason, the inclusion of signed error, AE, PE and Bland–Altman analysis strengthened the validation of the tape method in the present study [12,26].

The MAPE of approximately 5% suggests that the measuring tape had good practical accuracy overall, since MAPE expresses the average prediction error as a percentage of the observed value and is commonly used to quantify relative prediction accuracy [14,27]. For many routine management purposes, such as monitoring growth trends, identifying animals with poor development or making broad nutritional decisions, this level of error may be acceptable, particularly when the objective is to follow changes in body weight over time rather than to obtain an exact weight at a single point [1,5]. However, the magnitude of error may be more relevant in situations requiring precise live-weight information,

such as calculating medication dosage, determining sale weight, assessing eligibility for specific production categories or evaluating experimental growth performance. Accurate live-weight estimation is important for treatment dosing, feeding decisions and slaughter or marketing decisions [28]. In those cases, scale weighing remains preferable whenever available, because calibrated scales are considered the reference method for determining LW [5,28].

Age was the main factor associated with tape accuracy. The tape slightly overestimated live weight in younger calves but increasingly underestimated it in older calves. Repeated-measures models confirmed this pattern, with SiE decreasing by 5.74 kg per 100 days. AE also increased with age, showing greater practical disagreement. This bias is biologically plausible because body proportions change during growth [5,8]. Recent calf-weight prediction work has shown that body weight can be reliably estimated from heart girth measurements, but also that age and morphometric development must be considered when developing prediction models [8]. Similarly, validation studies of heart-girth tapes in calves emphasise that tape estimates should be assessed against scale weights rather than assumed to be constant across animals and ages [5]. More broadly, cattle body-weight prediction studies show that age category, sex and breed can influence the relationship between linear body measurements and LW [21].

The Bland–Altman analysis supported this interpretation by showing proportional bias. Tape error became more negative as mean body weight increased, indicating that underestimation was not random across the weight range. This finding has practical implications because Bland–Altman analysis is specifically intended to show whether differences between two measurement methods vary according to the magnitude of measurement [11,12]. Similar concerns have been reported in body-weight estimation studies in cattle, where agreement between indirect estimates and scale weight may be poorer in heavier animals [7,29]. If the tape is used to monitor younger calves, it may provide sufficiently close estimates for routine management. However, when used in older or heavier calves, the same tape may underestimate LW, potentially leading to incorrect decisions. For example, animals may be considered lighter than they actually are, which could affect nutritional planning, treatment dosage or marketing decisions [28]. Future work could address this by developing age- or weight-specific correction equations for Minhota calves, as body-weight prediction from linear measurements is known to be affected by age, sex and breed categories [21].

Dam parity was associated with signed error and absolute error, with calves from primiparous dams showing less underestimation than those from multiparous dams. However, this finding should be interpreted cautiously because the primiparous group was relatively small. Parity may influence birth weight, early growth, maternal performance and neonatal metabolism [9,10]. Dam parity did not strongly modify the relationship between thoracic perimeter and live weight. The weak tendency may reflect calf size or age distribution; studies with primiparous dams are needed.

A strength of the present study is that it used repeated records from the same calves and accounted for this structure in the statistical analysis. This is important because repeated observations from the same animal are not independent; observations within an individual tend to be correlated and this correlation should be accounted for to obtain valid inference [30,31]. Using calf identity as the clustering variable allowed a more appropriate assessment of age, sex and dam parity effects on tape error. Another strength was the use of complementary accuracy measures: SiE for bias, AE for kg disagreement, APE for relative accuracy, and Bland–Altman analysis for proportional bias [12,16,17].

The study was limited to Minhota calves, so findings may not apply to other breeds or systems. Because body conformation affects the relationship between thoracic perimeter and live weight, tape accuracy should be validated within each target population. Few records from primiparous dams reduced power to detect parity effects. The study assessed existing tape estimates but did not derive a Minhota-specific equation; balanced longitudinal validation at fixed ages is needed.

The findings of this study are relevant for producers and technicians working with Minhota calves. Measuring tapes provide a low-cost method for estimating live weight when scales are unavailable and for monitoring growth trends. However, age-dependent bias means tape estimates should not replace scale weights. Accuracy was greater in younger calves, while underestimation increased in heavier animals; age-related correction factors may improve use.

5. Conclusions

The thoracic measuring tape provided a practical and generally accurate estimate of LW in Minhota calves, showing a very strong association with scale-measured LW and an average APE of approximately 5%. These findings support its use as a simple, low-cost tool for routine growth monitoring, particularly in farm situations where access to calibrated scales is limited.

However, tape-estimated weight should not be considered fully interchangeable with scale-measured weight. The tape showed a small average underestimation of LW, and its accuracy was clearly influenced by calf age. In younger calves, tape estimates were close to scale-measured values in terms of bias and absolute kg error, whereas older and heavier calves showed increasing underestimation and larger absolute error. However, relative error was highest in the youngest calves, because small kg differences represented a larger proportion of their body weight. This age-related bias was the main limitation of the method and indicates that caution is needed when using the tape for precise management decisions, such as treatment dosing, marketing or experimental evaluation.

Sex and dam parity had comparatively limited effects on tape accuracy after accounting for calf age and repeated measurements. The tendency toward lower underestimation in calves from primiparous dams should be interpreted with caution because this group was relatively small.

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Abbreviations

The following abbreviations are used in this manuscript:

APE	Absolute Percentage Error
AR	Absolute Error
LW	Live Weight
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MSIE	Mean Signed Error
PE	Percentage Error
RMSE	Root Mean Squared Error
SiE	Signed Error

Appendix A. Relationship Between Thoracic Perimeter and Tape-Estimated Live Weight

The thoracic measuring tape used in this study provided a live-weight estimate directly from the measured thoracic perimeter. Therefore, the tape-estimated live weight was not calculated by the authors from a newly developed prediction equation. Instead, it represented the value read from the measuring tape at the time of measurement.

Figure A1 shows the relationship between thoracic perimeter and the live-weight value provided by the measuring tape. This figure is included only to document the internal perimeter-to-weight conversion pattern of the tape. It should not be interpreted as an agreement analysis between the tape-estimated and scale-measured live weight. Agreement between the two methods is assessed in the main text using the direct comparison with scale-measured live weight, Bland–Altman analysis and error-based statistics.

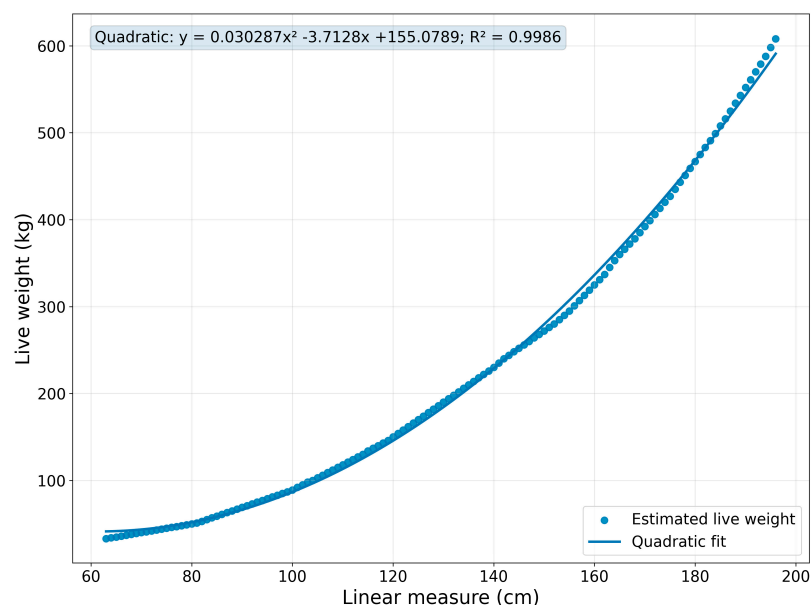


Figure A1. Relationship between thoracic perimeter and tape-estimated live weight provided by the measuring tape. Each point represents one weighing record. Tape-estimated live weight refers to the value read directly from the thoracic measuring tape after measuring the calf's thoracic perimeter. The fitted curve describes the tape's perimeter-to-weight conversion pattern and is presented for documentation purposes only; it does not represent agreement between tape-estimated and scale-measured live weight.

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