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Three-dimensional imaging to estimate *in vivo* body and carcass chemical composition of growing beef-on-dairy crossbred bulls

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A B S T R A C T

The dynamics of cattle body chemical composition during growth and fattening periods determine animal performance and beef carcass quality. The aim of this study was to estimate the empty body (**EB**) and carcass chemical composition of growing beef-on-dairy crossbred bulls (Brown Swiss breed as dam with Angus, Limousin or Simmental as sire) using three-dimensional (**3D**) imaging. The 3D images of the cattle's external body shape were recorded *in vivo* on 48 bulls along growth trajectory (75–520 kg BW and 34–306 kg hot carcass weight [**HCW**]; set 1) and on 70 bulls at target market slaughter weight, including 18 animals from set 1 (average 517 ± 10 kg BW and 289 ± 10 kg HCW; set 2). The linear, circumference, curve, surface and volume measurements on the 3D body shape were determined. Those predictive variables were used in partial least square regressions, together with the effect of the sire breed whenever significant ($P < 0.05$), with leave-one-out cross-validation to estimate water, lipid, protein, mineral and energy mass or proportions in the EB and carcass. Mass and proportions were determined directly from *postmortem* grinding and chemical analyses (set 1) or indirectly using the 11th rib dissection method (set 2). In set 1, bulls' BW and HCW were estimated via 3D imaging, with root mean square error of prediction (**RMSEP**) of 12 kg and 6 kg, respectively. The EB and carcass chemical component proportions were estimated with RMSEP from 0.2% for EB minerals (observed mean 3.7 ± 0.2%) to 1.8% for EB lipid (11.6 ± 4.2%), close to the RMSEP found for the carcass. In set 2, the RMSEP for estimation via 3D imaging was 9 kg for BW and 6 kg for HCW. The EB energy and protein proportions were estimated, with RMSEP of 0.5 MJ/kg fresh matter (10.1 ± 0.8 MJ/DM) and 0.2% (18.7 ± 0.7%), respectively. Overall, the estimations of chemical component proportions from 3D imaging were slightly less precise for both sets than the mass estimations. The morphological traits from the 3D images appeared to be precise estimators of BW, HCW as well as EB and carcass chemical component masses and proportions.

Implications

Monitoring the *in vivo* dynamics of body and carcass composition is mandatory in beef production systems for the enhancement of profits. In this study, the morphological traits measured *in vivo* by three-dimensional imaging in beef-on-dairy crossbred bulls and calibration against reference *postmortem* chemical analyses, enabled a fair estimation of the masses and proportions of empty body and carcass chemical components (water, lipids, proteins, minerals and energy). Further development of three-dimensional imaging technology would provide on-farm access to the BW, carcass yield and composition of live cattle and support the implementation of precision livestock farming for enhancing efficiency and profitability.

Introduction

The dynamics of the accretion and mobilization of body lipids and proteins widely affect the performance of beef and dairy cattle, whereas body reserve management influences the animals' health

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and welfare (Roche et al., 2009). Additionally, knowledge of the chemical composition (water, lipids, proteins, minerals and energy contents) of farm animals is of interest to precisely estimate animal nutrient requirements and adapt their regimes to improve feed efficiency—and thus, economic performance. The reference method for body chemical composition quantification is through *postmortem* grinding and chemical analyses (Yan et al., 2009; Fernandes et al., 2010; Castilhos et al., 2018). Nonetheless, such methodologies are costly, destructive of edible meat and obviously cannot be performed kinetically for the same individual along a productive cycle, so, their use is usually restricted to research purposes. Alternatively, the estimation of body composition in living animals is mainly realised by visual or palpation assessment of subcutaneous tissue thickness, resulting in classification or scoring, such as the body condition score (**BCS**) for body fatness (Roche et al., 2009). The estimation of body chemical composition is also feasible thanks to body morphological traits recorded manually on living cattle (Yan et al., 2009; Fernandes et al., 2010; De Paula et al., 2013). The *in vivo* estimation of body reserves is also performed thanks to imaging technologies. Ultrasound measurements of subcutaneous tissue thickness have been developed as a non-invasive technique that allows the monitoring of body and carcass composition (Bergen et al., 2005; Schröder and Staufenbiel, 2006; Castilhos et al., 2018). Other imaging technologies allow the estimation of body composition using X-ray (i.e. dual-energy X-ray absorptiometry or computer tomography) or magnetic resonance imaging (Scholz et al., 2015; Lerch et al., 2021). However, limitations in the implementation of these technologies prevent their wider use on-field. Ultrasound imaging is a method with moderate precision and may be sensitive to the operator effect (Schröder and Staufenbiel, 2006), while X-ray and magnetic resonance imaging technologies are precise but expensive. Besides, they require safety measures (due to radiation or magnetic field) and have not been yet adapted to large animals (i.e. with BW higher than 200 kg; Scholz et al., 2015; Xavier et al., 2023).

In this context, rapidly developing three-dimensional (**3D**) imaging technology offers new perspectives that can outstrip the limitations of manual or other imaging technology measurements. Pioneer developments have raised interest in 3D imaging to determine the BW of dairy cows easily and precisely (Le Cozler et al., 2019a; Le Cozler et al., 2022a) and other species (e.g. cattle, pig, goat or sheep, as reviewed by Dohmen et al., 2021, and Wang et al., 2021). In addition to being non-invasive, 3D imaging also avoids direct contact with animals, leading to greater safety and easier handling, and it opens the door for high-throughput automatic phenotyping of morphological traits (Le Cozler et al., 2022b). In growing or finishing cattle, 3D imaging has already been successfully developed, estimating average daily gain (Cominotte et al., 2020), carcass grading (Miller et al., 2019), empty body (**EB**) lipid proportion (Gomes et al., 2016) and EB and carcass chemical composition on a reduced set of culled cows (Xavier et al., 2022a). To the best of our knowledge, the calibration of *in vivo* 3D imaging technology for the estimation of EB and carcass water, lipid, protein, mineral and energy content has not yet been performed in growing beef cattle.

The aim of this study was to calibrate and determine the precision of *in vivo* 3D imaging for the estimation of EB and carcass chemical composition in growing crossbred bulls from the three most common beef-on-dairy crossbreeds in specialised beef farming systems of Switzerland (Lerch et al., 2020). Beef-on-dairy crossbreeding is indeed currently of growing interest worldwide due to its economic and environmental advantages (Faverdin et al., 2022). Preliminary results of the present study have previously been presented as a conference abstract (Xavier et al., 2022b).

Material and methods

Animals and diets

The study was performed at the experimental farm of Agroscope (Posieux, Switzerland) from 5 February 2020 to 4 February 2021. A total of 100 crossbred bulls (Brown Swiss as dam crossed with Angus, Limousin or Simmental as sire) were purchased at the age of 31.5 (± 7.9, SD) days, corresponding to 73.6 ± 8.3 kg BW from commercial farms across Switzerland. These three types of beef-on-dairy crossbreeding are the most commonly performed in Swiss dairy farms. Until 160 kg of BW, the bulls received milk (26 kg of milk powder per calf in total over the first 7 weeks), hay, concentrate feedstuffs (rearing and prefattening calf feed) and maize silage progressively introduced from 100 kg BW. From 160 kg BW until slaughter, they received one of two isoenergetic and isoproteic total mixed rations (**TMR**). The TMR A was composed of maize silage (38% DM basis) and grass silage (36%) complemented with a concentrate feedstuff made of peas, barley, corn gluten meal, soybean meal, vitamins and minerals (26%). The TMR B was composed of maize silage (38%), alfalfa-grass silage (34%), straw (1%) and a concentrate feedstuff made of fava beans, triticale, corn gluten meal, soybean meal, vitamins, and minerals (27%). Throughout the experiment, the bulls were housed in a free-stall barn with a straw bedding area and had free access to fresh water. All procedures regarding their management followed the Swiss national regulations (Order 455.1 of the Swiss federal laws, 2008), including access to outdoor pens after reaching 160 kg BW.

Two bulls per crossbreed receiving TMR A were slaughtered at 72 ± 10, 163 ± 5, 258 ± 12, 347 ± 11 and 421 ± 8 kg BW. Among the remaining 70 bulls slaughtered at 517 ± 10 kg, 34 bulls received TMR A [Angus sire: n = 11; Simmental sire: n = 11; Limousin sire: n = 12] and 36 bulls received TMR B [Angus sire: n = 12; Simmental sire: n = 12; Limousin sire: n = 12].

For the analyses, data recorded on the bulls were split into two sets:

- Set 1: 48 bulls (n = 16 of each crossbreed) slaughtered at different BW along growth trajectory, including 18 of those slaughtered at 517 kg BW, for which direct *postmortem* measurements of body chemical composition were available (see below).
- Set 2: 70 crossbred bulls (n = 23 with Angus sire, n = 24 with Limousin sire and n = 23 with Simmental sire) slaughtered at 517 kg BW, for which either direct measurements (n = 18) or indirect estimation (through 11th rib dissection method, see below; n = 52) of body chemical composition was available.

Serial slaughter procedure (set 1) aimed to determine the chemical composition at different stages of growth (growth trajectory) and included 18 bulls from the set 2 (terminal point). The average slaughter weight of the bulls in set 2 corresponds to the weight currently targeted in Switzerland for the fattening beef carcass market (Lerch et al., 2020) (set 2, terminal point).

Scoring from the Swiss carcass grade (**CH-TAX**) was rated on each alive animal for the fat cover and the conformation. The scoring was always realized by the same trained operator from 0 to 8 days prior slaughter. Briefly, the grading of the cold carcass is realized on a scale of 1 – 5 for fat and conformation according to the CH-TAX classification system (Order 916.341.22 of Swiss federal laws 1999, last update 2003). The score for the conformation class is given in the form of the letters C H T A X and some intermediate classes. For the purposes of evaluation, these letters have been transformed into numbers as follows: C = 5, H = 4, T+ = 3.5, T = 3, T- = 2.5, A = 2 and X = 1).

Slaughter, empty body and carcass chemical composition measurements

Procedure for the bulls of set 1 (growth trajectory; n = 48)

On the day of slaughter, the bulls had no access to feed from 0000 h and were slaughtered between 0800 and 1100 h at the experimental slaughterhouse of Agroscope (Posieux, Switzerland) in accordance with legally defined procedures (Order 455.1 of the Swiss federal laws, 2008), as previously described by Driesen et al. (2022) and Xavier et al. (2022a). Two blood samples (250 g each) were collected at exsanguination and stored at −20°C. Ground homogenates of the left half-carcass, hide and the rest of the EB (head, lower legs, visceral organs and adipose tissues) were processed separately using an industrial crusher (Granulator type PS 4–5, Pallmann Industries, Pompton Plains, United States of America), a mixer (Mixer type MIX 165, Talsa, Spain) and a cutter device (Cutter DMK 45 C, DMS-Maschinensysteme, Saarbrücken, Germany) on the frozen matrix as described by Driesen et al. (2022) and Xavier et al. (2022a). Two 250 g aliquots were then sampled and stored at −20°C. Frozen samples were lyophilised (duplicate determination) and finely ground with liquid nitrogen using a knife mill (Grindomix GM200, Retsch, Düsseldorf, Germany) pending chemical analyses. The DM (3 h at 105°C), lipid (ISO 6492:1999, petroleum ether extraction with a Büchi Speed Extractor E-916, Flawil, Switzerland), protein (ISO 16634-1:2008, N × 6.25 by Dumas combustion thermal conductivity with a Leco Trumac CNS, Mönchengladbach, Germany) and energy (ISO 9831:1998, adiabatic calorimetry with an oxygen bomb calorimeter, AC600 Leco, Mönchengladbach, Germany) content as well as minerals expressed from crude ash content (furnace at 550°C until constant weight) were determined. Constant weighing and reweighing procedures before and after every cooling and freezing step were ensured, and any weight loss from the initial preslaughter BW at the slaughterhouse was assumed to be water loss.

Procedure for the remaining bulls of set 2 (terminal point; n = 52)

The remaining 52 bulls not included in set 1 had no access to feed from 0000 h and were slaughtered between 0700 and 1100 h at a commercial slaughterhouse (Marmy Viande en gros SA, Estavayer-le-Lac, Switzerland) following legally defined procedures (Order 455.1 of the Swiss federal laws, 2008). The 11th rib from the left half-carcass was sampled after the carcass chilling at 4°C for 24h. Rib muscles, adipose tissues and bones were dissected and weighed to the nearest 0.1 g according to Geay and Béranger (1969) and Xavier et al. (2022a). The rib tissue masses and proportions were used together with BW or hot carcass weight (**HCW**) and slaughterhouse grading (CH-TAX grading, Order 946.341, Annex 1 Swiss federal laws, 2003) to estimate the EB and carcass chemical composition using the equations noted as "C" reported in Tables 2 and 3 in Lerch et al. (2023) and in Supplementary Table S1. Mineral proportions and masses in the EB and carcass were not estimated because of the lower precision of the predictive equations from the 11th rib dissection. These equations were developed for bulls of the same crossbreeds with the same BW (507 ± 19 kg), including the 18 bulls used in both sets 1 and 2 of the present study.

Three-dimensional imaging measurements

From 20 min to 3 h (set 1) or 3–4 days (set 2) before slaughter, body shape was captured using a 3D surface scanner (Morpho 3D, 3D Ouest, Lannion, France) similar to the equipment and method described and presented by Le Cozler et al. (2019a). Point clouds from the scanner were processed using Metrux® software (3D Ouest). Metrux® is designed to interactively compute measurements on 3D data (point clouds or triangle meshes). Some 3D processing tools are also included in the software to clean the point cloud data (e.g. eraser, outlier filter, surface reconstruction from point cloud). From the resulting 3D mesh images, the point cloud data were filtered, and the 3D mesh surface was reconstructed using Poisson surface reconstruction (Kazhdan et al., 2006) using Metrux® V4 software. Then, different measurements were carried out using Metrux® V8 software, as illustrated in Fig. 1 and described in Table 1. The measurements included straight Euclidian distances, convex hull or curve length in a plane, geodesic distances, surface area and volumes. They are presented by the breed of sire and class of BW in Supplementary Tables S2 and S3.

Statistical analyses

All statistical analyses were performed with R software (version 3.6.3, R Core Team, 2020). Type 3 ANOVA analyses using the R package "car" (Fox and Weisberg, 2019) and least squares means and Tuckey adjustment from the "emmeans" package (Lenth, 2020) were performed on the chemical composition and 3D variables to study sire breed (n = 3) and BW effects (as class (n = 6) for the set 1, and as a numeric variable in set 2) and their interaction. The TMR effect and its interaction with the sire breed was tested for set 2, but since it was not significant (P > 0.10), it was removed from the model. Pearson's correlation between the proportions of water and lipids in the EB and carcass was realised using the function "cor.test" (R package "stats" of R Core Team, 2020).

Separately for sets 1 and 2, a first series of linear regressions with leave-one-out cross-validation were set up to predict EB and carcass chemical composition from BW and sire breed using the "caret" package (Kuhn, 2021). Similarly, a second series of linear regressions was obtained after adding the CH-TAX fat and conformation scores at BW and the sire breed. The EB and carcass composition estimation by 3D variables, BW and sire breed were tested using partial least square regressions (**PLS**) with the leave-one-out cross-validation method (R package "pls" of Mevik et al., 2020). Predictive variables in the PLS regressions were scaled and standardised using the "Scale" option and integrated as latent variables to explain the dependent variable (i.e. EB or carcass chemical component mass or proportion). For each model, the optimal number of latent variables was based on the lowest RMSE of prediction (**RMSEP**). The coefficients of each 3D variable for the number of latent variables selected were analyzed to remove the variables with the smallest standardised coefficient. This step was repeated until the RMSEP increased again. The final model selected was the one with the lowest RMSEP. The RMSEP, R^2 (variance explained by the model) and residual CV of prediction (**rCVP**; ratio of RMSEP to the mean of the dependent variate) are presented for each selected model. Simplified models were developed for the models including more than 20 3D variable in the final model by variable selection as described previously. The significance level was defined as a probability value (P) equal to or lower than 0.05. Statistical trends were considered at 0.05 < $P \leq$ 0.10.

Results

Empty body and carcass weights and chemical composition

Set 1 along growth trajectory

The HCW and carcass yields are presented in Table 2 and their chemical composition is in Table 3. The HCW varied from 34 kg to 306 kg. The hot carcass yield was 56 ± 3%. The proportions of lipids

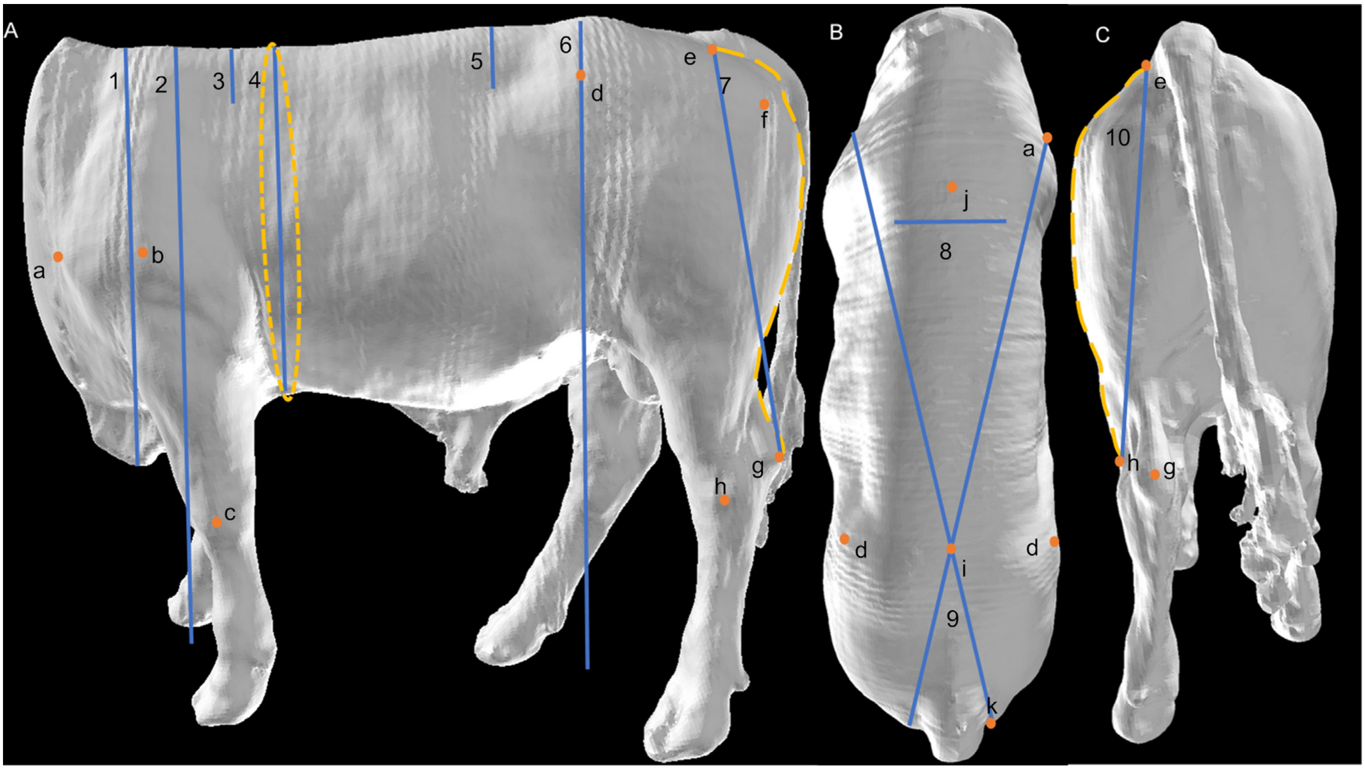

Fig. 1. Morphological measurements from three-dimensional images of beef-on-dairy crossbred bulls. The anatomical points (a–k) and measurements (1–10) are described in Table 1.

and energy in the EB were much more variable across individuals (CV of 36 and 18%, respectively) than water, proteins and minerals proportions (CV of 3–6%). Similar variations were noted in terms of carcass chemical composition. A strong negative correlation was observed between water and lipid proportions in both the EB ($r \leq -0.989$, $P < 0.001$) and the carcass ($r \leq -0.986$, $P < 0.001$). The relationships between lipid and water in carcass resulted in R^2 = 0.972, RMSE = 0.6% and rCV = 5.9% and in the EB, 0.978, 0.6 and 5.3%, respectively (Fig. 2) The fat-free EB (EB total mass – EB lipid mass) composition was fairly constant and corresponded to 75.0 ± 1.1% water, 20.8 ± 1.0% proteins and 4.2 ± 0.2% minerals. The fat-free carcass composition was similar to the fat-free EB composition.

Table 3 presents the least-squares means for EB and carcass chemical composition. Chemical composition differed between each BW class. At the end point with an average BW of 517 kg, Angus crossbred bulls had higher ($P \leq 0.10$) content of lipids (EB: 18.5 vs 14.6 and 12.5%, carcass: 16.4 vs 12.9 and 10.7%) and energy (EB: 11.3 vs 9.9 and 9.2 MJ/kg, carcass: 10.7 vs 9.4 and 8.6 MJ/kg) than Limousin or Simmental crossbreeds. Conversely, Angus crossbred bulls had lower water proportion (EB: 60.3 vs 63.3 and 64.9%, $P \leq 0.05$; carcass: 62.2 vs 64.1 and 65.1%, $P \leq 0.10$) than Limousin or Simmental crossbreeds.

Set 2 at commercial slaughter weight (terminal point)

The HCW averaged 289.3 ± 10.0 kg with a CV of 3.4% and carcass yield of 56 ± 2% (Table 2). The EB and carcass lipid proportions (Table 4) were the most variable, with a CV of 17% for the EB and 19% for the carcass, while water and protein proportions had a similar CV (around 3%) for both carcass and EB. Energy contained per kg of EB or hot carcass had a CV of 9% or 8%, respectively. Angus crossbred bulls were ($P < 0.01$) fatter (17.3% of lipids in the EB and 15.9% in the carcass), with more energy stored (10.9 MJ/kg in the EB and 10.4 MJ/kg in the carcass) than Simmental crossbreeds (EB: 13.3% and 9.6 MJ/kg and carcass: 11.2% and 8.9 MJ/kg for lipids and energy, respectively). Limousin crossbreeds were intermediate (EB: 14.6% and 10.0 MJ/kg and carcass: 12.6% and 9.2 MJ/kg for lipids and energy, respectively).

Estimation of empty body and carcass chemical composition by three-dimensional imaging

The morphological traits of the bulls gathered from 3D imaging from sets 1 and 2 are presented in Supplementary Tables S2 and S3. Limousin crossbred bulls presented a larger format (hind quarter and partial surfaces, heart girth, hip height and length between the middle of the hip and the hock) than Angus and Simmental crossbreeds along the growth trajectory (set 1). The same differences in body traits were found at the end point for the Limousin crossbred bulls (terminal point; set 2).

Relative importance of three-dimensions' variables in the estimative models

The PLS model equations are presented in Tables 5 and 6, and in Supplementary Tables S4, S5 and S6. Only the direct length of thigh side and hip height were significant in both data sets for the estimation of EB and carcass component mass. For the EB chemical mass estimation, six additional 3D variables (length of thigh back, length of shoulder side, wither height, direct length of shoulder side, partial volume and BW) had significant contributions in both sets 1 (growth trajectory) and 2 (terminal point). For carcass masses, the number of 3D variables in common between the two datasets was less important (shoulder thickness, heart girth and ratios (shoulder side and heart girth)/partial volume). Partial volume was significant in most models, with positive and high standardised coefficient for EB and carcass chemical component masses and proportions along growth trajectory (set 1), but seldom at commercial slaughter weight (set 2).

Table 1
Description of the morphological measurements from three-dimensional images of beef-on-dairy crossbred bulls.

Morphological traits	Unit	Description	Points[1]	Measurements[1]
Anatomical points-				
Above the knee	–		c	
Base of the tail	–		e	
Hip point	–		d	
Hock	–		g	
Insertion of the tarsal region	–		h	
Ischium	–		k	
Middle of scapula	–		b	
Middle of the hip width	–		i	
Shoulder point	–		a	
Trochanter	–		f	
Wither	–		j	
Measurements				
Linear measurements				
CD	m	Chest depth (to the back of the shoulder)	–	4
DL	m	Diagonal length between the shoulder point and the opposite ischium	a–k	9
DT	m	Dewlap thickness between the middle of the shoulder point at the top and bottom	–	1
HG	m	Heart girth (to the back of the shoulder)	–	4
HH	m	Hip height (from the middle of the hip to the ground)	i	6
HW	m	Hip width between both hip points	d	–
LHH	m	Length between the left hock and the middle of the hip width	i–g	–
LHI	m	Length between the hip and the ischium	d–k	–
LTH	m	Length between the left trochanter and the middle of the hip width	i–f	–
LWH	m	Length between the wither height and the middle of the hip width	j–i	–
LWI	m	Length between the wither and the left ischium	j–k	–
ST	m	Scapula thickness between the spline and the scapula (from lateral view)	–	3
SW	m	Scapula width between both scapula at the back of the wither	–	8
TSP	m	Thickness between the spine and the paralumbar cavity	–	5
WH	m	Wither height from the wither to the ground	j	2
WS	m	Width between the middle of both shoulders	b	–
aLTB	m	Maximum of the curve of the thick back (between the base of the tail and the hook)	e–g	7
aLTS	m	Maximum of the curve of the thick side (between the base of the tail and the tarsal region)	e–h	10
aLSS	m	Maximum of the curve of the shoulder side (between the wither and above the knee)	j–c	–
dLTB	m	The direct length between the base of the tail and the hook	e–g	7
dLTS	m	The direct length between the base of the tail and the tarsal region	e–h	10
dLSS	m	The direct length between the wither and above the knee	j–c	–
LTB	m	Length of the thick back (between the base of the tail and the hook)	e–g	7
LTS	m	Length of the thick side (between the base of the tail and the tarsal region)	e–h	10
LSS	m	Length of the shoulder side (between the wither and above the knee)	j–c	–
TB	m	Length of the thick back divided by the direct length between the base of the tail and the hook	e–g	7
TS	m	Length of the thick side divided by the direct length between the base of the tail and the tarsal region	e–h	10
SS	m	Length of the shoulder side divided by the direct length between the wither and above the knee	j–c	–
Areas under the curve				
aTB	m^2	Area under the curve of the thick back (between the base of the tail and the hook)	e–g	7
aTS	m^2	Area under the curve of the thick side (between the base of the tail and the tarsal region)	e–h	10
aSS	m^2	Area under the curve of the shoulder side (between the wither and above the knee)	j–c	–
Surfaces				
HS	m^2	Hindquarter surface from the hip point	d	–
FS	m^2	Frontquarter surface from the shoulder point to the back of shoulder	a	4
PS	m^2	Partial surface from the shoulder point	a	–
Volumes				
HV	m^3	Hindquarter volume from the hip point	d	–
FV	m^3	Frontquarter volume from the shoulder point to the back of shoulder	a	4
PV	m^3	Partial volume from the shoulder point	a	–

[1] As reported in Fig. 1.

For the estimation of EB and carcass chemical proportions, direct length of the thigh side and chest depth were the most significant 3D variables in sets 1 and 2. Six additional variables (hip height, back length, hip-trochanter length, shoulder thickness and areas under the curve for the shoulder side and the thigh back) and two ratios (hip thickness on the hindquarter volume and shoulder thickness on the partial volume) were included in most of the PLS models for both sets for the EB proportion. BW and partial volume, when significant in the models, had high standardised coefficients. In set 1, they had a positive coefficient, except for the partial volume for the EB water proportion estimative model, but conversely, in set 2, the partial volume coefficient for models estimative of water and protein proportions was negative.

Estimation of the chemical composition in set 1 along growth trajectory

Along the growth trajectory, the PLS model statistics for the estimations of BW, HCW and carcass yield as well as the chemical proportions in the EB and carcass from 3D imaging variables are presented in Table 5. Supplementary Table S4 presents the details of the equations, and Supplementary Table S5 presents the PLS model statistics for the chemical masses. The BW, HCW and carcass yields were estimated from 3D variables and the sire breed effect on the intercept of PLS regressions models with RMSEP of 12.0, 5.7 kg and 1.2%, respectively. Simplified model for the estimation of the HCW reduced the number of variables from 40 to 18 with a slight increase of the RMSEP of +5.0 kg and +2.6 point for the rCVp.

Table 2
Age, BW, empty BW and carcass weight of beef-on-dairy crossbred bulls with Brown Swiss as dam and Angus, Simmental or Limousin as sire from serial slaughter along growth trajectory (set 1) and at commercial slaughter weight (set 2).

Item	Mean	SD	Minimum	Maximum
Serial slaughter (set 1, n = 48)				
Slaughter age (days)	236	111	25	395
Slaughter BW (kg)	348	160	58	522
Digesta content (kg)	36	16	1	59
Empty BW (kg)	311	145	56	477
Hot carcass weight (HCW, kg)	194	92	34	306
Cold carcass weight (kg)	190	91	33	301
Carcass yield (HCW / BW, %)	55.6	2.9	49.8	62.6
Final slaughter weight (set 2, n = 70)				
Slaughter age (days)	352	27	286	427
Slaughter BW (kg)	517	10	491	539
Average daily gain (kg/d)[1]	1.49	0.13	1.12	1.77
HCW (kg)	289	10	271	318
Carcass yield (HCW / BW, %)	56.0	1.6	52.2	60.2

Abbreviation: HCW = Hot carcass weight.
[1] Average daily gain between 154 and 517 kg BW.

The BW with the sire breed effect linear models allowed estimation of the EB chemical component proportions, with RMSEP varying from 0.2% for minerals to 1.5% for water, while the protein proportion estimation was not significant ($P > 0.10$). In comparison, estimations of EB and carcass chemical composition were improved when the CH-TAX fat or conformation grades were used with decreases of the RMSEP from −0% for EB mineral proportions to −0.4% for EB lipid proportions, corresponding to decreases of the rCVp from −0.2 point for EB mineral proportion, to −2.2 point for EB lipid proportion. The BW associated with the fat score allowed an estimation of the EB protein proportions with an RMSEP of 0.6% and an rCVp of 3.1%. The carcass mineral proportion was estimated by the BW and conformation score with an RMSEP of 0.3% and an rCVp of 6.6%. When 3D variables were added to BW in PLS regressions, improvement of precision was observed for the estimation of the chemical proportions when compared to the BW alone linear regressions, with reduced RMSEP (e.g. −0.1% for EB lipids; −0.5% for EB water) and rCVP (−0.3 to −0.7 point). Moreover, 3D-based models had slightly lower RMSEP for the EB and carcass water and mineral proportions compared to the models developed with the use of CH-TAX (RMSEP decreasing up to −0.2% and rCVp from −0.3 to −0.4 point). For other components in carcass and EB, the RMSEP from PLS models including 3D variables was either increased (energy) or did not change (proteins), compared to models with CH-TAX. Estimation of the carcass protein proportions was not reliable because of the poor relationship with BW alone ($r = -0.09$, $P = 0.56$; not presented), with BW associated with the CH-TAX scores or with 3D variables. The PLS models with a reduction of the number of 3D measurements had slightly increased RMSEP value (i.e. lowered the precision; +0.8% maximum) for EB and carcass water, lipid and energy proportions, compared to the models with full 3D variables. None relationships were determined for the EB and carcass protein and mineral proportions.

For the chemical masses, the R^2 was not a fair indicator of the model precision and denoted the wide variability within the group. A comparison of the RMSEP and the rCVp was used instead to qualify the precision of the models and compare them with each other in the following result description. The BW with the sire breed effect linear models allowed estimation of the EB and carcass chemical component masses, with RMSEP ranging from 0.8 kg for carcass minerals to 9.2 kg for EB water and with rCVP ranging from 3.4% for EB water to 22.7% for carcass lipids. Relationships with BW and CH-TAX improved the precision compared to the relationship with BW alone (RMSEP was decreased from −0 kg for carcass and EB mineral to −0.8 kg for EB lipid; rCVp decreased from −0.1 point for EB and carcass water to −2.1 points for EB lipid). The same applied to the estimation of energy in the EB and in the carcass with a decrease up to −30 MJ for the RMSEP or −1.1 points for the rCVp. None improved relationship can be established with the CH-TAX scores alone, or associated with the BW and the sire breed for EB and carcass protein masses. Estimations of EB and carcass chemical component masses were improved when 3D variables were added to BW in PLS regressions. The RMSEP was decreased from −0.2 kg for EB and carcass mineral masses up to −3.2 kg for EB lipid mass and −0.9 kg for carcass lipid mass. When compared to CH-TAX−based models, for the energy content, RMSEP was decreased by −52 MJ in carcass, but increased by +5MJ in EB. Accordingly, a decrease in the rCVP of −0 to −5.7 points was recorded for EB chemical component masses in the EB and carcass, except for EB energy (+0.2 point) and carcass water (+0.3 point).

Estimation of the chemical composition in set 2 at commercial slaughter weight

At commercial slaughter weight (set 2), BW, HCW, carcass yield and EB and carcass chemical component proportions estimative PLS model statistics are presented in Table 6. Additionally, Supplementary Table S4 presents details of the model equations and Table S6 presents the model statistics for chemical component masses estimative. Estimation of BW and HCW via 3D variables resulted in RMSEP of 8.9 and 6.3 kg, respectively. The carcass yield was estimated with RMSEP of 1.1%. The number of variables for these models was comprised between 8 and 14.

The BW alone was not significant ($P > 0.10$) for estimating the proportions of chemical components in the EB or carcass, except for the EB protein proportion, with RMSEP of 0.3%, corresponding to a 1.7% rCVP. Conversely, including CH-TAX fat or conformation grades allowed to estimate all the EB and carcass chemical component proportions. For the EB protein proportions, the RMSEP was close to the one of the linear regression with the BW alone corresponding to a 1.6% rCVP. For the lipid and water proportions, RMSEP was between 1.1% for the carcass water and 1.5% for EB lipid, corresponding to rCVp from 1.7% for carcass water up to 10.3% for EB lipid. Energy was estimated with a rCVp of 5.1% for EB and 5.0% for carcass. Compared to the models with CH-TAX, the use of 3D variables in PLS models decreased the RMSEP for EB protein proportion of −0.1%. Moreover, 3D−based models allowed a fair estimation for all the carcass chemical components and the EB energy proportions, with similar RMSEP than those obtained for the CH-TAX fat or conformation scores−based model. The RMSEP and the rCVp were only slightly increased with the use

Table 3
Least-squares means for the chemical compositions in mass and proportions of crossbred bulls with Brown Swiss as dam and Angus, Limousin or Simmental as sire along growth trajectory from 58 kg to 522 kg BW (set 1, n = 48).

		BW class (mean ± SD, kg)							*P*-value		
Chemical component	Sire breed	72 ± 10	163 ± 5	258 ± 12	347 ± 11	421 ± 8	507 ± 10	SEM	Sire breed	BW class	Sire breed × BW class
Empty body											
Water (kg)	Angus	51.5^{a}	99.5^{b}	154.2^{c}	201.7^{d}	242.2^{e}	274.5^{f}	8.0	0.966	<0.001	0.057
	Limousin	42.9^{a}	101.5^{b}	150.6^{c}	199.6^{d}	242.8^{e}	296.4^{g}				
	Simmental	54.7^{a}	99.9^{b}	149.6^{c}	211.0^{d}	250.2^{e}	290.9^{g}				
Lipids (kg)	Angus	5.1^{a}	9.9^{abc}	23.5^{abcde}	46.5^{efg}	53.1^{fgh}	84.1^{i}	6.7	0.971	<0.001	0.023
	Limousin	3.3^{a}	8.7^{ab}	20.3^{abc}	32.5^{cdef}	48.5^{fg}	68.3^{h}				
	Simmental	5.1^{a}	8.4^{ab}	21.2^{abcd}	30.1^{bcdef}	43.9^{defg}	56.0^{gh}				
Proteins (kg)	Angus	13.1^{a}	26.8^{b}	41.0^{c}	57.0^{d}	68.2^{e}	80.7^{f}	2.4	0.861	<0.001	0.042
	Limousin	10.6^{a}	26.2^{b}	41.2^{c}	56.7^{d}	69.1^{e}	87.8^{g}				
	Simmental	13.7^{a}	25.4^{b}	39.2^{c}	57.6^{d}	70.4^{e}	85.0^{fg}				
Minerals (kg)	Angus	2.7^{a}	5.2^{ab}	8.6^{bc}	11.7^{cd}	14.0^{de}	16.3^{ef}	1.1	0.975	<0.001	0.993
	Limousin	2.4^{a}	5.4^{ab}	8.5^{bc}	11.6^{cd}	14.2^{def}	17.2^{f}				
	Simmental	3.0^{a}	5.2^{ab}	7.9^{bc}	11.2^{cd}	13.8^{de}	16.3^{ef}				
Energy (MJ)	Angus	499^{a}	996^{abc}	$1\,874^{de}$	$3\,126^{fgh}$	$3\,672^{hi}$	$5\,132^{k}$	229	0.937	<0.001	0.015
	Limousin	378^{a}	937^{ab}	$1\,746^{cd}$	$2\,592^{efg}$	$3\,529^{hi}$	$4\,652^{j}$				
	Simmental	514^{a}	917^{a}	$1\,734^{bcd}$	$2\,504^{def}$	$3\,358^{gh}$	$4\,126^{i}$				
Water (%)	Angus	71.1^{g}	70.5^{fg}	67.7^{cdefg}	63.9^{abc}	64.1^{bcd}	60.3^{a}	1.3	0.524	<0.001	0.172
	Limousin	72.2^{g}	71.7^{g}	68.3^{defg}	66.4^{bcdef}	64.7^{bcde}	63.3^{b}				
	Simmental	71.5^{g}	71.9^{g}	68.7^{efg}	68.2^{cdefg}	66.1^{bcdef}	64.9^{bcd}				
Lipids (%)	Angus	7.0^{ab}	7.0^{ab}	10.2^{abcd}	14.7^{cde}	14.1^{cde}	18.5^{e}	1.6	0.797	<0.001	0.092
	Limousin	5.6^{a}	6.1^{ab}	9.1^{abc}	10.8^{abcd}	12.9^{cd}	14.6^{d}				
	Simmental	6.6^{ab}	6.0^{ab}	9.7^{abc}	9.7^{abc}	11.6^{bcd}	12.5^{cd}				
Proteins (%)	Angus	18.0^{ab}	19.0^{ab}	18.0^{ab}	18.0^{ab}	18.1^{ab}	17.7^{a}	0.5	0.469	0.270	0.156
	Limousin	17.8^{ab}	18.5^{ab}	18.7^{ab}	18.9^{ab}	18.4^{ab}	18.7^{ab}				
	Simmental	17.9^{ab}	18.3^{ab}	18.0^{ab}	18.6^{ab}	18.6^{ab}	19.0^{b}				
Minerals (%)	Angus	3.7^{a}	3.7^{a}	3.8^{a}	3.7^{a}	3.7^{a}	3.6^{a}	0.2	0.809	0.374	0.992
	Limousin	4.0^{a}	3.8^{a}	3.9^{a}	3.9^{a}	3.8^{a}	3.7^{a}				
	Simmental	3.9^{a}	3.8^{a}	3.6^{a}	3.6^{a}	3.7^{a}	3.6^{a}				
Energy (MJ/kg fresh matter)	Angus	6.9^{ab}	7.1^{abc}	8.2^{abcde}	9.9^{efg}	9.7^{def}	11.3^{g}	0.5	0.627	<0.001	0.087
	Limousin	6.3^{a}	6.6^{a}	7.9^{abcd}	8.6^{bcdef}	9.4^{def}	9.9^{f}				
	Simmental	6.7^{a}	6.6^{a}	8.0^{abcd}	8.1^{abcde}	8.9^{cdef}	9.2^{def}				
Carcass											
Water (kg)	Angus	32.6^{a}	58.6^{b}	92.6^{c}	127.6^{d}	149.8^{de}	174.1^{fg}	6.5	0.712	<0.001	0.156
	Limousin	26.2^{a}	63.4^{b}	95.7^{c}	127.6^{d}	153.7^{e}	190.9^{h}				
	Simmental	33.7^{a}	58.9^{b}	88.7^{c}	130.4^{d}	157.8^{ef}	184.6^{gh}				
Lipids (kg)	Angus	2.7^{a}	5.5^{ab}	13.7^{abcd}	25.5^{def}	29.0^{efg}	46.6^{h}	3.7	0.983	<0.001	0.012
	Limousin	1.8^{a}	5.2^{ab}	11.5^{abc}	18.4^{cde}	25.9^{def}	38.3^{g}				
	Simmental	2.6^{a}	4.8^{ab}	11.0^{abc}	16.5^{bcde}	23.7^{cdef}	29.9^{f}				
Proteins (kg)	Angus	8.5^{a}	16.5^{b}	25.2^{c}	36.0^{d}	41.8^{de}	50.8^{f}	1.9	0.821	<0.001	0.124
	Limousin	6.7^{a}	16.4^{b}	25.4^{c}	36.2^{d}	43.6^{e}	55.8^{g}				
	Simmental	8.7^{a}	15.4^{b}	24.1^{c}	35.5^{d}	43.9^{e}	53.0^{fg}				
Minerals (kg)	Angus	1.8^{a}	3.6^{ab}	5.8^{bc}	8.1^{cd}	10.3^{def}	11.9^{ef}	0.9	0.98	<0.001	0.978
	Limousin	1.5^{a}	3.7^{ab}	5.9^{bc}	8.5^{cd}	10.4^{def}	12.9^{f}				
	Simmental	1.9^{a}	3.6^{ab}	5.5^{bc}	8.1^{cd}	10.0^{de}	11.9^{ef}				
Energy (MJ)	Angus	304^{a}	592^{abc}	$1\,126^{de}$	$1\,850^{fgh}$	$2\,123^{hi}$	$3\,023^{j}$	132	0.939	<0.001	0.007
	Limousin	226^{a}	583^{ab}	$1\,046^{cde}$	$1\,590^{fg}$	$2\,065^{hi}$	$2\,780^{j}$				
	Simmental	306^{a}	548^{ab}	996^{bcd}	$1\,493^{ef}$	$1\,964^{gh}$	$2\,401^{i}$				
Water (%)	Angus	71.4^{gh}	69.8^{efgh}	67.3^{bcdefg}	64.8^{abcd}	64.6^{abc}	61.4^{a}	1.3	0.388	<0.001	0.246
	Limousin	72.2^{h}	71.5^{gh}	69.1^{defgh}	66.8^{bcdef}	65.6^{bcde}	64.1^{b}				
	Simmental	71.7^{h}	71.2^{fgh}	68.6^{cdefgh}	68.4^{cdefgh}	66.9^{bcdef}	65.9^{bcd}				
Lipids (%)	Angus	6.0^{abc}	6.5^{abcd}	9.9^{abcdef}	13.0^{efg}	12.5^{efg}	16.4^{g}	1.5	0.861	<0.001	0.094
	Limousin	4.9^{a}	5.9^{ab}	8.2^{abcde}	9.6^{abcdef}	11.1^{cdef}	12.9^{f}				
	Simmental	5.6^{ab}	5.8^{ab}	8.5^{abcde}	8.6^{abcde}	10.0^{bcdef}	10.7^{def}				
Proteins (%)	Angus	18.6^{ab}	19.6^{b}	18.3^{ab}	18.3^{ab}	18.0^{ab}	17.9^{a}	0.5	0.065	0.635	0.099
	Limousin	18.4^{ab}	18.5^{ab}	18.3^{ab}	18.9^{ab}	18.6^{ab}	18.8^{ab}				
	Simmental	18.5^{ab}	18.6^{ab}	18.6^{ab}	18.6^{ab}	18.6^{ab}	18.9^{ab}				
Minerals (%)	Angus	3.9^{a}	4.2^{a}	4.2^{a}	4.1^{a}	4.4^{a}	4.2^{a}	0.3	0.956	0.648	0.995
	Limousin	4.1^{a}	4.2^{a}	4.3^{a}	4.5^{a}	4.5^{a}	4.3^{a}				
	Simmental	4.1^{a}	4.3^{a}	4.3^{a}	4.2^{a}	4.2^{a}	4.3^{a}				
Energy (MJ/kg fresh matter)	Angus	6.7^{abc}	7.1^{abcd}	8.2^{bcdefg}	9.4^{fgh}	9.2^{efg}	10.7^{h}	0.5	0.587	<0.001	0.080
	Limousin	6.2^{a}	6.6^{abc}	7.5^{abcde}	8.3^{cdefg}	8.8^{defg}	9.4^{g}				
	Simmental	6.5^{ab}	6.6^{abc}	7.7^{abcdef}	7.8^{abcdef}	8.3^{cdefg}	8.6^{efg}				

[a-k] Within a chemical component (Sire breed × BW class), least-square means with different letters tend to differ at $P \le 0.10$.

of the 3D variables compared to the CH-TAX models for EB water and lipid proportions (RMSEP increased by +0.1% and rCVp by +0.3 point). Few simplified PLS models with a reduced number of 3D variables were determined because the initial number of 3D variables in the full model was most of the time under 20. Accordingly, only EB protein and energy proportions were determined with simplified model (number of variables divided by 4 or 5) with increases of RMSEP by 0.1% compared to the full 3D variables model.

The BW alone in linear regressions was not significant (P > 0.10) for estimating lipid and mineral masses, while water, protein masses and energy content were estimated with RMSEP of 5.3

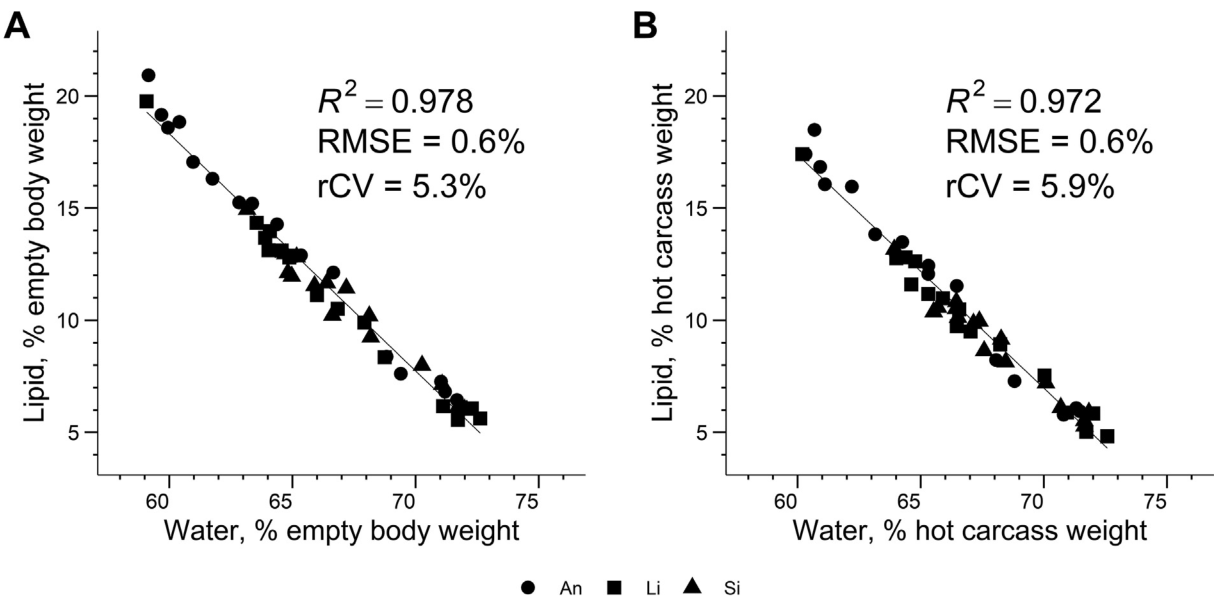

Fig. 2. Relationship between lipid and water proportions in the empty body (A) and hot carcass (B) of 48 beef-on-dairy crossbred bulls with Brown Swiss as dam and Angus (An), Limousin (Li) or Simmental (Si) as sire (along growth trajectory; set 1) presented with R^2, RMSE and residual CV (rCV).

Table 4
Least-squares means for the chemical compositions in masses and in proportions of crossbred bulls with Brown Swiss as dam and Angus, Limousin or Simmental as sire at commercial slaughter weight 517 ± 10 kg BW (set 2, *n* = 70).

	Sire breed				*P*-value		
Chemical component	Angus	Limousin	Simmental	SEM	Sire breed	BW	Sire breed × BW
Empty body							
Water (kg)	283.3[a]	298.9[b]	302.3[c]	4.9	0.025	<0.001	0.040
Lipids (kg)	77.5[c]	66.5[b]	59.7[a]	8.4	0.018	0.330	0.024
Proteins (kg)	82.9[a]	88.7[b]	90.0[c]	1.3	0.815	<0.001	0.806
Energy (MJ)	5 007[c]	4 639[b]	4 421[a]	287	0.030	0.087	0.040
Water (%)	61.3[a]	63.4[b]	64.3[c]	1.3	0.006	0.060	0.009
Lipids (%)	17.3[c]	14.6[b]	13.3[a]	1.8	0.006	0.082	0.009
Proteins (%)	17.8[a]	18.8[b]	19.2[c]	0.3	0.489	0.001	0.513
Energy (MJ/kg fresh matter)	10.9[c]	10.0[b]	9.6[a]	0.6	0.006	0.151	0.009
Carcass							
Water (kg)	176.9[a]	190.5[b]	187.5[b]	6.0	0.032	<0.001	0.031
Lipids (kg)	44.4[c]	36.9[b]	32.9[a]	4.1	0.025	0.893	0.036
Proteins (kg)	50.8[a]	55.7[c]	54.5[b]	1.5	0.201	<0.001	0.161
Energy (MJ)	2 943[c]	2 731[b]	2 572[a]	152	0.037	0.071	0.053
Water (%)	62.0[a]	64.5[b]	65.6[c]	1.2	0.029	0.180	0.039
Lipids (%)	15.9[c]	12.6[b]	11.2[a]	1.5	0.026	0.234	0.036
Proteins (%)	17.9[a]	18.8[b]	19.0[b]	0.3	0.712	0.362	0.766
Energy (MJ/kg fresh matter)	10.4[c]	9.2[b]	8.9[a]	0.5	0.029	0.645	0.039

[a–c] Within a chemical component (Sire breed × BW), least-square means with different letters tend to differ at $P \leq 0.10$.

and 6.5 kg water, 1.3 and 1.6 kg proteins and 308 and 162 MJ energy in the EB and the carcass, respectively. With the CH-TAX fat score associated with the sire breed, lipid masses were estimated in the EB with RMSEP of 7.2 kg and rCVp of 10.8% and in the carcass with RMSEP of 3.8 kg and rCVp of 10.0%. For the other components, the estimation with the fat or conformation scores improved the relationships, when compared to BW alone, with a RMSEP decrease by −0 to −1.1 kg and an rCVp decrease by −0.1– −0.4 point. The use of 3D variables in addition to BW in PLS regressions slightly improved the estimation of EB protein mass and carcass lipid mass and energy content, when compared to CH-TAX−based models. Conversely, the precision did not change for the estimation of the carcass protein mass, and slightly decreased for the EB water and lipid masses, and carcass water mass with a RMSEP increased from +0.1 kg for carcass water mass to +0.3 kg for EB water mass. For the EB energy content, RMSEP was also higher for the PLS with 3D variables, than for the CHTAX−based model (increased by +32 MJ).

Discussion

Novel aspects of the present investigation include the calibration of estimative equations of EB and carcass chemical composition based on 3D imaging technology in beef-on-dairy crossbred bulls. The EB and carcass chemical composition of Angus crossbreeds significantly differed from that of Limousin and Simmental crossbreeds. Such a difference between genotypes was already included in the models developed by Miller et al. (2019), who also estimated BW and carcass weight from 3D images, in more than 1 000 beef cattle. Miller et al. (2019) split the beef cattle breeds

Table 5
Estimations of empty body and carcass weights and chemical component proportions from BW and fat and conformation scores (linear regressions) or body morphological traits measured on three-dimensional (3D) images [partial least square (PLS) regressions] of crossbred bulls with Brown Swiss as dam and Angus, Limousin or Simmental as sire along growth trajectory from 58 kg to 522 kg BW (set 1, n = 48).

	BW linear regression[1]			BW & CHTAX linear regression[2]			Full 3D measurements PLS regression[3]				Simplified 3D measurements PLS regression[4]			
Item	RMSEP	rCVP	R^2	RMSEP	rCVP	R^2	Variable number	RMSEP	rCVP	R^2	Variable number	RMSEP	rCVP	R^2
BW (kg)							8	12.0	3.4	0.997	Not determined[5]			
Hot carcass weight (kg)							40	5.7	2.9	1.000	18	10.7	5.5	0.994
Carcass yield (%)							8	1.2	2.2	0.875	Not determined[5]			
Empty body proportions (%, unless stated)														
Water	1.5	2.2	0.857	1.2	1.8	0.909	31	1.0	1.5	0.990	6	1.5	2.3	0.890
Lipids	1.9	16.1	0.795	1.5	13.3	0.860	19	1.8	15.4	0.864	7	2.0	17.2	0.823
Proteins	Not significant ($P > 0.10$)			0.6	3.1	0.151	22	0.6	3.1	0.098	None satisfactory relationship[6]			
Minerals	0.2	5.8	0.053	0.2	5.6	0.116	27	0.2	5.2	0.202	None satisfactory relationship[6]			
Energy (MJ/kg)	0.6	7.2	0.839	0.5	5.8	0.896	24	0.6	6.9	0.906	10	0.6	7.2	0.867
Carcass proportions (%, unless stated)														
Water	1.4	2.0	0.844	1.2	1.8	0.881	31	0.9	1.3	0.993	19	1.5	2.3	0.870
Lipids	1.6	16.0	0.793	1.4	14.0	0.841	34	1.0	9.8	0.992	14	1.7	16.8	0.836
Proteins	Not significant ($P > 0.10$)			Not significant ($P > 0.10$)			None satisfactory relationship				None satisfactory relationship[6]			
Minerals	Not significant ($P > 0.10$)			0.3	6.6	0.048	22	0.3	6.2	0.070	None satisfactory relationship[6]			
Energy (MJ/kg)	0.6	7.0	0.820	0.5	6.1	0.861	19	0.5	6.3	0.896	18	0.6	6.8	0.873

Abbreviations: CHTAX = Cold Carcass Swiss score according to CH-TAX classification system (order 916.341.22 of Swiss federal Laws 1999, last update 2003) applied on living animals with a grading for fat on a scale 1–5 and for conformation with letters scale translate as numeric values (C = 5, H = 4, T+= 3.5, T = 3, T-= 2.5, A = 2, X = 1), RMSEP = root mean square error of prediction, rCVP = residual CV of prediction, ratio of RMSEP to the mean of the dependent variate.

[1] Sire breed effect on the intercept was significant ($P < 0.05$) and included in regressions, at the exception of empty body minerals (not significant, $P > 0.10$).

[2] Carcass fat score evaluated on living cattle prior slaughter, BW and sire breed were significant ($P < 0.05$) and included in regressions, at the exception of empty body proteins (sire breed not significant and removed), minerals (only carcass conformation score was significant and included), and carcass minerals (only BW and carcass conformation score were significant and included).

[3] Sire breed effect on the intercept was significant ($P < 0.05$) and included in regressions. The BW was not significant ($P > 0.10$) and not included in full 3D measurements PLS regressions, at the exception of empty body proteins ($P < 0.05$, included in the regression).

[4] Sire breed effect on the intercept was significant ($P < 0.05$) and included in regressions.

[5] Already less than 20 3D measurement variables were included in the full 3D measurements PLS regressions.

[6] For the estimation of empty body and carcass proteins and minerals, no satisfactory PLS regression can be fitted with less than 20 3D measurement variables.

Table 6

Estimations of empty body and carcass weights and chemical component proportions from BW and fat and conformation scores (linear regressions) or body morphological traits measured on three-dimensional (3D) images [partial least square (PLS) regressions] of crossbred bulls with Brown Swiss as dam and Angus, Limousin or Simmental as sire at the final slaughter weight (terminal point) 517 ± 10 kg BW (set 2, n = 70).

	BW linear regression[1]			CHTAX linear regression[2]			Full 3D measurements PLS regression[3]				Simplified 3D measurements PLS regression[4]			
Item	RMSEP	rCVP	R^2	RMSEP	rCVP	R^2	Variable number	RMSEP	rCVP	R^2	Variable number	RMSEP	rCVP	R^2
BW (kg)							8	8.9	1.7	0.416	Not determined[5]			
Hot carcass weight (kg)							14	6.3	2.2	0.782	Not determined[5]			
Carcass yield (%)							11	1.1	2.1	0.622	Not determined[5]			
Empty body proportions (%, unless stated)														
Water	Not significant ($P > 0.10$)			1.2	1.8	0.625	19	1.3	2.1	0.669	Not determined[5]			
Lipids	Not significant ($P > 0.10$)			1.5	10.3	0.613	15	1.6	10.6	0.690	Not determined[5]			
Proteins	0.3	1.7	0.770	0.3	1.6	0.805	25	0.2	1.3	0.940	7	0.3	1.7	0.836
Energy (MJ/kg)	Not significant ($P > 0.10$)			0.5	5.1	0.626	30	0.5	5.4	0.679	5	0.6	5.7	0.594
Carcass proportions (%, unless stated)														
Water	Not significant ($P > 0.10$)			1.1	1.7	0.692	13	1.1	1.7	0.788	Not determined[5]			
Lipids	Not significant ($P > 0.10$)			1.3	9.8	0.725	11	1.3	10.0	0.802	Not determined[5]			
Proteins	Not significant ($P > 0.10$)			0.3	1.4	0.758	12	0.3	1.4	0.828	Not determined[5]			
Energy (MJ/kg)	Not significant ($P > 0.10$)			0.5	5.0	0.700	11	0.5	5.1	0.792	Not determined[5]			

Abbreviations: CHTAX = Cold Carcass Swiss score according to CH-TAX classification system (order 916.341.22 of Swiss federal Laws 1999, last update 2003) applied on living animals with grading for fat on a scale 1–5 and for conformation with letters scale translate as numeric values (C = 5, H = 4, T+= 3.5, T = 3, T-= 2.5, A = 2, X = 1), RMSEP = root mean square error of prediction, rCVP = residual CV of prediction, ratio of RMSEP to the mean of the dependent variate.

[1] Sire breed effect on the intercept was significant ($P < 0.05$) and included in empty body protein regression.

[2] Carcass fat score evaluated on living cattle prior to slaughter and sire breed was significant ($P < 0.05$) and included in regressions. Carcass conformation score, BW and sire breed were significant only for the empty body proteins estimation and included in the corresponding estimative regression.

[3] Sire breed effect on the intercept was significant ($P < 0.05$) and included in regressions. The BW was not significant ($P > 0.10$) and was not included in full 3D measurements PLS regressions.

[4] Sire breed effect on the intercept was significant ($P < 0.05$) and included in regressions. The BW was only significant ($P < 0.05$) for empty body water estimation and included in the corresponding estimative regression.

[5] Already less than 20 3D measurement variables were included in the full 3D measurements PLS regressions.

according to their origin, between British (Angus and other very early maturing breeds) and continental (Simmental and Limousin) beef breeds. The consistency of the morphological differences for some traits in the present study (e.g. the length between the hock and the hip or the thickness between the spine and the paralumbar cavity) between these two groups also underlined the effect of the sire breed.

The BW was fairly estimated from the body traits extracted from 3D images. For both sets, 8 variables were involved in the models but these 3D variables differed. The width between the middle of both shoulders, the heart grith and the chest depth were the only variables in common between both models. Volumes (partial, frontquarter or hindquarter) were more involved as raw measurement in the model for set 1 (growth trajectory) whereas they were used as denominators in ratios with other variables in the model of set 2 (commercial slaughter weight; terminal point). The results obtained for the set 1 (rCVP of 3.4%) were similar to the residual CV (rCV; ratio of the RMSE on the mean of the dependant variable) of 3.7% reported by Le Cozler et al. (2019b) when estimating Holstein dairy cow BW using the same 3D-imaging equipment. Previous studies using different 3D imaging devices obtained a wider range of precision (rCV) when estimating cattle BW (Kuzuhara et al., 2015; Gomes et al., 2016; Martins et al., 2020). Only Kamchen et al. (2021) found a lower rCV than in the present study for BW estimation, with a value of 0.1% in Nellore heifers. Conversely, from the 3D top view of the cattle's back, Gomes et al. (2016) found a higher rCV of 4.5% for Angus bulls and 4.0% for Angus × Nellore bulls, while Kuzuhara et al. (2015) obtained an rCV of 5.7% from a quarter 3D view of Holstein cows. Finally, Martins et al. (2020), also using a 3D top view to determine the BW of Holstein cows and heifers, found an rCV of 5.6%, providing a better estimation than from lateral 3D body view (rCV of 10.0%). The HCW was also determined with high precision via 3D imaging in the present study, with the rCV varying between 2.2 and 2.9%, which was much lower than the rCV reported by Gomes et al. (2016), which was 4.8% for Angus and 5.4% for Angus × Nellore bulls. Similarly, lower precision was found by Miller et al. (2019) for steers and heifers of several breeds, with an rCV of 4.7% using a linear regression and of 4.1% using an artificial neural network. Yan et al. (2009) reported an rCV of 5.6% for Holstein cows with morphological traits recorded manually. The variability and orders of magnitude of BW and carcass weight across studies may explain, at least partly, such a wide range of rCV values. Besides, the higher precision in the present study and that of Le Cozler et al. (2019b) can be explained by the accuracy of the device and the type of information collected with the 3D cameras, since volumes were measured directly from the images. In the case of Kamchen et al. (2021), they were calculated from a top view with similar higher performance. Moreover, differences between studies may also be partly explained by the area scanned with the 3D cameras, the image posttreatment and the statistical approaches. Cominotte et al. (2020) noticed this latter difference and concluded that multiple linear regressions were less precise than PLS ones. Similarly, Miller et al. (2019) concluded that an artificial neural network (including sex and cattle type) showed better performance than a linear regression (also including sex and cattle type), with a decreased RMSE of 9 kg when using an artificial neural network compared to a linear regression. Finally, taking into account the breed and the sex effects also improved the precision of models, as previously highlighted by Miller et al. (2019).

The use of the fat or conformation score (CH-TAX classification scheme) graded from living animals, together with the BW and sire breed, allowed a fair estimation of the chemical components of EB and carcass. However, the grading of live animals was realized with a classification only in use in Switzerland and equivalent to the EUROP carcass grading system in the European Union. Indeed, BCS rating in growing beef cattle is not so common, whereas there is not necessarily a clear consensus on which grid scale to use, in comparison to the better "normalization" achieved worldwide for BCS in dairy cows (Bazin et al., 1984; Roche et al., 2009) or sheep (Russel et al., 1969). Additionally, such kinds of grading based on visual appreciation and palpation are realised by an expert, the scoring can be further affected by an operator effect, which added subjectivity to the linear regression model developed in the present study. The quantification of the inter-operator variability in CH-TAX or BCS scoring, and further bias on the estimation of body composition from predictive equations, would deserve further investigations.

For the estimations of water and protein masses in the EB or carcass along growth trajectory (set 1), adding 3D variables over BW alone into PLS models improved the precision of the estimation only slightly, while the estimation of the other EB chemical component masses were improved consistently. In previous studies estimating body chemical composition from cattle morphological traits recorded manually, lipid mass was the most frequently studied component (Fernandes et al., 2010; De Paula et al., 2013; Fonseca et al., 2017). These studies reported an rCV range comparable to the rCVP obtained in the present investigation (e.g. for EB or carcass lipid masses from 10.9 to 15.8% in Fernandes et al. (2010) vs 9.9–18.6% in the present study). Fonseca et al. (2017) used hook bone width and rib depth traits to estimate lipid mass, while Fernandes et al. (2010) and De Paula et al. (2013) added shrunk BW to improve estimation models. From models including only heart girth, Yan et al. (2009) found in Holstein cows an rCV varying between 37 and 39% for EB lipid mass estimation, but when BCS was added to heart girth, the rCV decreased by nearly 9 points. These authors also reported estimations of EB protein and mineral mass using heart girth and length from the tip of the shoulder to the edge of the pin bone, with rCVs of 4.8 and 13.8%, respectively. For EB energy, the rCV was 14.6% when BCS was included together with heart girth and length from the tip of shoulder to the edge of the pin bone in the estimative model (Yan et al., 2009), a precision still lower than in the present study. For the estimation of carcass water mass, Castilhos et al. (2018), using hip height, shrunk BW and age, found an rCV of 3.5%, remarkably close from the one for set 2 in the present study (3.2%). As for masses in the present study, the estimations of chemical component proportions in the EB and carcass using 3D recorded morphological traits were precise along growth trajectory (set 1) and at commercial final slaughter weight (set 2). Even with a reduced number of 3D variables used (between 6 and 19), the estimation of the EB and carcass chemical proportions remained fair and close to the complete model. Previously, Gomes et al. (2016), from morphological traits recorded with 3D images of beef bulls, estimated the EB lipid proportion with an RMSE of 1.4% and an rCV of 10.0%, the latter being slightly lower than the rCVs recorded in the present study (10.5–15.4%).

Conclusion

The 3D imaging of the external whole-body shape of living growing crossbred bulls enabled precise estimation of the phenotypes of interest, such as BW, HCW and carcass yield, as well as detailed EB and carcass chemical composition. When 3D-recorded morphological traits were added to BW as estimative variables along growth trajectory in PLS models, the predictive capabilities for EB and carcass composition were consistently improved over BW alone, and comparable with BW and CH-TAX in linear regression models. Among the morphological traits, the variables related to the hind quarter were more often of interest and significantly entered the predictive models than those from the front quarter. Nonetheless, the final adjusted PLS models still included variables from the front quarter and the rest of the body shape. Even when the number of 3D variables was reduced in simplified 3D PLS models (less than 20 3D variables), models included variables from all the parts of the body. The *in vivo* 3D imaging method combines technical simplicity, non-invasiveness, non-subjectivity and safety for animals and operators (compared to CH-TAX and BCS), and can be performed dynamically throughout an animal's lifespan. Differences in the body morphology and chemical composition between crossbreeds were also highlighted, and further developments allowing the classification of breeds and crossbreds into categories may simplify estimative models based on 3D imaging variables. The present study is a first step in the development of 3D imaging-based models. An external validation would be needed to confirm the present results and improve the further use of these models. For practical implementation on the farm or in the slaughterhouse, the 3D prototype device used in the present study should be adapted by focusing, for example, on a selected section of the animal body (e.g. the hind quarter). Additionally, further automatization of image acquisition and post-treatment is required to ultimately allow the use of 3D imaging tools as a standard for precision livestock farming in the future.

Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.animal.2024.101174.

Ethics approval

The animal experimentation was set in accordance with Swiss guidelines for animal welfare under authorization no. 2020_03_FR delivered by the Swiss Federal Committee for Animal Care and Use (Canton Fribourg, Switzerland).

Data and model availability statement

The individual data of EB and carcass chemical composition are available in the Data INRAE repository at https://doi.org/10.57745/EK4FFP. Other 3D beef cattle measurement data can be accessed from the authors upon reasonable request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

None.

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