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Estimating body weight in conventional growing pigs using a depth camera

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ABSTRACT

Automated body weight (BW) estimation can be a useful tool for continuous monitoring of growth in commercial pigs, whereas deviations could indicate welfare problems. We validated a depth camera for BW estimation in 251 conventional growing pigs on two farms. Scale-based BW of individual pigs was used as gold standard (Farm 1: 107 pigs, BW range: 16–130 kg, recorded on three days; Farm 2: 144 pigs BW range: 20–114 kg, recorded on nine days). The camera was placed above the individual feeding station (Farm 1) or multi-partitioned feeder (Farm 2) and combined with a radio frequency identification system. Whenever a pig visited the feeding site, three-dimensional images were taken, and all individual daily images were used to calculate the median individual estimated BW. The pen estimated BW was calculated by taking the median of all daily picture estimates. A very high agreement (Concordance Correlation Coefficient >0.96) between scale-based BW and estimated BW was found on both farms at individual and pen level. Additionally, the individual-level and pen-level BW estimation errors of the median weight over the fattening period were low on both farms (≤3.6%). Yet, the camera's BW estimation performance decreased in pigs weighing >110 kg on Farm 1. Whereas, on Farm 2, the performance decreased when pigs weighed approximately 60 kg and were subjected to a typical dietary change, which potentially increased the competition for access to the multi-partitioned feeder and, consequently, limited body boundary detection.

1. Introduction

In pig production, the body weight (BW) of pigs is a crucial indicator of growth and readiness for market [1,2]. Additionally, knowledge on pig BW development is helpful to support animal welfare, including animal health, and optimise production efficiency [3]. Typically, on commercial farms, pig weighing is performed manually [4], which is considered the most accurate method to determine BW of animals [5]. However, in the European Union, pig farms have become larger in herd size over the last decades [6] and, hence, manual pig weighing involving handling constitutes a time-consuming and relatively stressful procedure to both pigs and stockmen [7].

Alternatively, BW of pigs can be indirectly determined from manual measurements (e.g., girth size, withers height; [7,8]), photogrammetry [9] and digital images (e.g., [10,11,2]) of pigs' body dimensions, due to a high, positive correlation between body dimensions and body mass [7]. Nevertheless, manual body dimension measuring is laborious and can be dangerous for humans and stressful for the animals, if handling is not done properly, leading to negative effects on the growth of young animals [12]. Furthermore, photogrammetric techniques typically require several cameras positioned at different locations taking simultaneous images of individual animals, which can be challenging to synchronise and expensive to implement on-farm. Whereas the image-analysis-based BW estimation can be an efficient, non-invasive method, this approach relies on visible light and the outcome can consequently be affected by the room lighting and the status of the pig skin (e.g., dark, stained, or dirty) [4]. To deal with these potential sources of errors, recent studies explored the use of depth cameras based on a structured infrared-light system, which provide three-dimensional (3D) images and eliminate errors arising from variations in skin colour and ambient light [13]. As 3D images can account for animal height, they may lead to more accurate BW estimates than two-dimensional (2D) images (e.g., [4,14,13,15]). Yet, the methods proposed by the cited studies required profound physical changes in the farm, such as modifications in the feeding site or pen corridor, to accommodate the equipment and avoid incomplete image viewpoint of the pigs and image

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quality issues arising from ambient light changes or unclear backgrounds. These physical interventions may be costly to farmers and require some habituation period for the animals prior to the beginning of the weight estimation.

Accordingly, we aimed to validate a commercially available depth camera providing 3D images for continuous BW monitoring of conventional growing pigs throughout the fattening period requiring minimal physical changes on-farm, hence requiring no habituation period for the pigs.

2. Materials and methods

This study was performed on two locations. The first location was a commercial farm in Gronau, Germany (Farm 1) between October and November 2021, and the second location was the experimental farm of the Department of Animal and Veterinary Sciences, Aarhus University, Viborg, Denmark (Farm 2) between September and November 2021. Ethical approval was not required for the procedures involving pigs on any of the two farms, as data was collected during standard management procedures and no additional measures were obtained for the study.

2.1. Animals, housing, and management

On both farms, pigs were raised under conventional husbandry conditions. On Farm 1, 107 Landrace × Large-White pigs were housed in 10 identical pens (9–11 pigs/pen; ≥1.03 m^2/pig; Table 1) spread across five rooms, on fully slatted floors (Fig. 1). Pigs were fed *ad libitum* with a commercial dry feed (until farm average of 57 kg: 16.2% crude protein, Select Delta 2; between 57-81 kg: 15.3% crude protein, Select Delta 4; above 81 kg: 13.8% crude protein, Select Delta 5; all produced by ABN, United Kingdom) using an IVOG® electronic feeding station (Hokofarm Group, The Netherlands). From a separate feeder, pigs could obtain fibre-rich feed (chopped straw mixed with straw pellets, in compliance with European Union and German animal welfare legislation) *ad libitum* by manipulating a chain. Water was available *ad libitum* from two drinking nipples, and enrichment consisted of a dry and fresh wooden block, a chain with plastic rings and in some pens one or more hosepipes. Pens were naturally illuminated through windows.

On Farm 2, 144 Yorkshire × Landrace pigs were housed in a finishing pig unit including 8 identical pens (9–18 pigs/pen; ≥0.73 m^2/pig; Table 1) with approximately 33% slatted, 33% drained and 33% solid floor (Fig. 2). Pigs were fed *ad libitum* with a commercial dry feed (until 60 kg: 14.8% crude protein, Svin Struktur E; above 60 kg: 15.5% crude protein, Svin Ideal Vox; both manufactured by DLG, Denmark), and the feeder containing three partitions were filled four times daily at 07:00 h, 11:00 h, 16:00 h and 20:00 h. Water was accessible *ad libitum* in two drinking cups. All pens were equipped with dry and fresh wooden sticks and a rubber ball as minimum pen enrichment in compliance with European Union and Danish animal welfare legislation. Artificial light was on from 06:00 h to 21:00 h (182 lx).

2.2. Body weight recording

Two types of BW data were recorded: scale-based BW (gold standard) and BW estimated by a depth camera (iDOL65, dol-sensors a/s, Aarhus, Denmark; technical information available on https://www.dol-sensors.com/wp-content/uploads/2019/11/EN-iDOL-65-Camera-TI-20210720.pdf). On Farm 1, the scale-based BW was recorded on three days throughout the fattening phase (BW range: 16–130 kg), first day in the morning and two last days in the afternoon (Table 1). On Farm 2, the scale-based BW was recorded on nine days throughout the fattening phase (BW range: 20–114 kg), all in the morning (Table 1). On each farm, all pigs per pen were moved into the corridor of the farm and individually walked into a calibrated digital weighing scale (Farm 1: W-2000, Welvaarts Weegsystemen, The Netherlands, accuracy: ±0.5 kg; Farm 2: MTW2-STACON, Schauer Agrotronic GmbH, Germany, accuracy: ±0.3 kg). On Farm 1, barn staff scanned pigs' radio frequency identification (RFID) ear tag and manually entered the individual BW on a computer, whilst, on Farm 2, pigs' RFID ear tag were read by the scale and automatically recorded the individual BW. Pen-level BW was calculated by taking the median of the individual BW of pigs per pen.

For the estimated BW, each pen was equipped with one depth camera placed above the individual feeding station (Farm 1; Fig. 1) or three-partitioned feeder (Farm 2; Fig. 2) at an approximate height of 2.2 m and worked in combination with an RFID system installed in the feeding sites (Farm 1: one RFID antenna per feeding station; Farm 2: one RFID antenna per feeder partition). Camera calibration was automatically performed upon camera installation and consisted of the camera storing its position and orientation in relation to the pen floor, as specified in its technical user guide (dol-sensors a/s, Aarhus, Denmark; https://www.dol-sensors.com/wp-content/uploads/2019/11/EN-604438-iDOL-65-Camera-TUG-20211203.pdf). On Farm 1, throughout the fattening phase, cameras were cleaned when they gave an error due to dirt on the lens. If a camera was moved during the cleaning process, it

Table 1
Breakdown on the number of pens, number of pigs, number of pigs per pen, scale-based body weight (BW), estimated BW, and number of images per pig used to obtain weight estimates at individual level and scale-based and estimated BW at pen level on each location (Farm 1, Germany; Farm 2, Denmark) and day.

Farm	Day	No. pens	No. pigs	No. pigs/pen	Individual level Scale-based BW (kg/pig)		Estimated BW (kg/pig)		No. images/pig		Pen level Scale-based BW (kg/pen)		Estimated BW (kg/pen)	
					Median	IQR[a]	Median	IQR[a]	Median	IQR[a]	Median	IQR[a]	Median	IQR[a]
1	1	9[b]	98	10–11[c]	24	21–27	—[d]	—[d]	—[d]	—[d]	24	23–25	24	23–25
(DE)	2	10	107	9–11[c]	73	68–80	74	67–81	256	201–327	73	71–74	73	71–74
	3	9[e]	97	9–11[c]	105	100–112	104	98–109	205	154–252	105	102–108	105	102–108
2	1	8	144	18	28	26–32	29	26–33	206	71–379	28	27–29	26	25–27
(DK)	2		144		36	33–39	36	33–40	268	140–507	36	35–37	35	33–36
	3		143	17–18[f]	42	38–45	42	39–46	582	375–783	42	41–43	40	38–40
	4		143		49	44–52	48	45–53	286	186–439	48	47–49	48	46–49
	5		143		56	52–60	55	51–61	272	168–426	55	54–57	54	52–55
	6		139	16–18[f]	63	58–69	62	58–70	216	106–348	64	62–66	63	60–66
	7		132	9–18[f]	72	65–77	69	64–76	116	70–223	72	69–74	71	69–72
	8		131	9–18[f]	80	73–87	79	72–86	107	60–198	81	77–83	80	76–83
	9		128	9–18[f]	89	82–96	84	78–92	112	71–206	89	88–92	87	85–90

[a] IQR=interquartile range.
[b] One camera was not yet calibrated, and the data was unavailable.
[c] All pens should contain 11 pigs. If only 10 or 9 were present, pigs had been removed due to sickness.
[d] Due to data storage malfunctioning, individual images and BW estimates were not available.
[e] One camera malfunctioned and the data was unavailable.
[f] All pens started with 18 pigs. If pens had fewer than 18 pigs, pigs had been removed due to sickness.

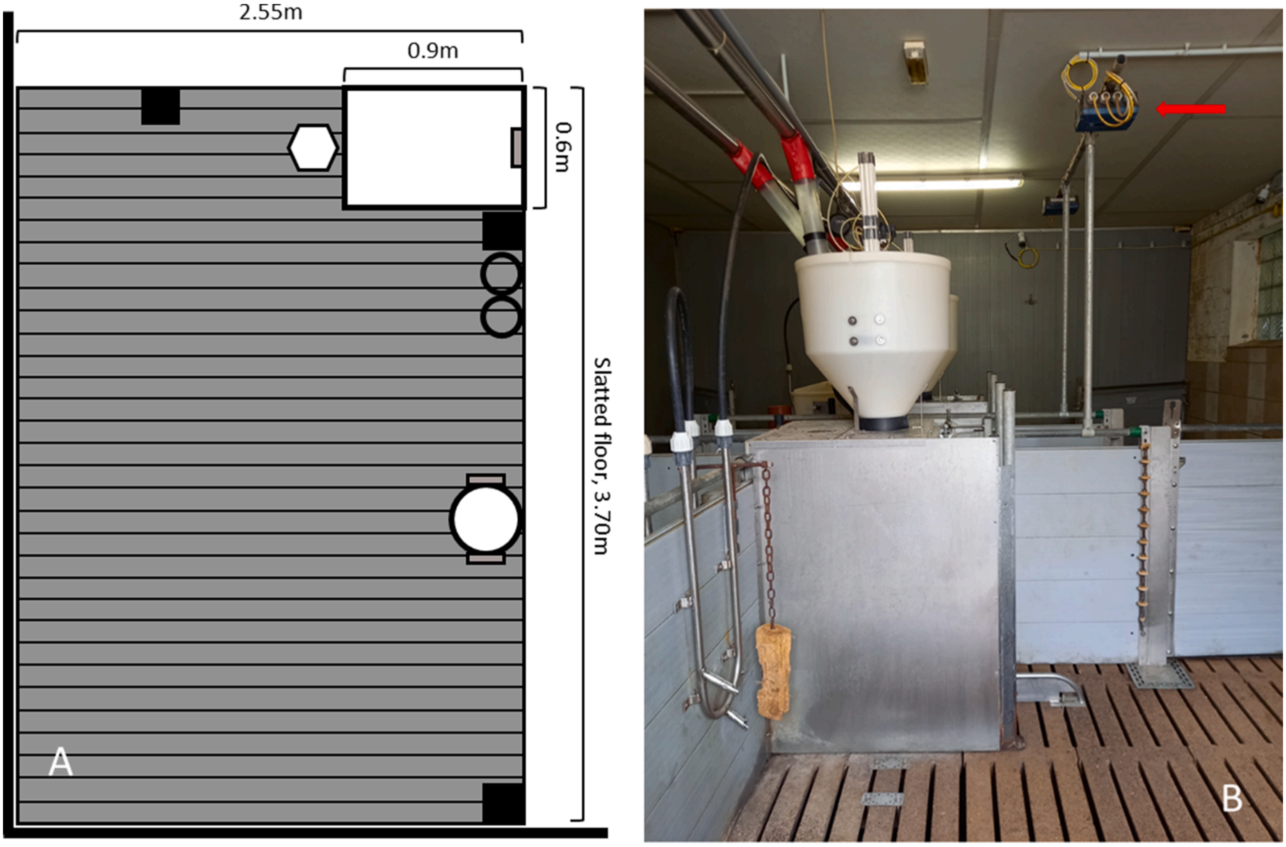

Fig. 1. (A) Illustration of the pen for fattening pigs on Farm 1. The single-space electronic feeding station is represented by the white rectangle, the iDOL65 3D camera by the white pentagon, the crude fibre station by the white circle, drinking cups by the black hollow circles, and the two solid black squares give the location of enrichment, which differed between pens. Half the pens were in the opposite configuration (feeder always located next to the door/corridor). (B) Illustration of the pen with the depth camera installed above the individual feeding station and indicated by the red arrow (credit: Jacinta D. Bus).

was recalibrated. On Farm 2, no camera cleaning or recalibration was performed. On Farm 1, the feeding station's construction was developed for only one pig to eat, and consequently be registered by the RFID system, at a time. On Farm 2, the RFID was configured to randomly switch between the three partitions and read once every second, hence each position could only be read once every 2 s. The camera took a 3D image at a 10-s interval on Farm 1 at individual and pen level, and on Farm 2 at pen level. On Farm 2, at individual level, the camera took a 3D image every 1 s.

A YOLO-based algorithm developed and trained by dol-sensors detected whether a pig was present in the picture and, if so, segmented out the individual pig. Segmented images were retained only if the pig was in standing position, close to the RFID reader and in full view (determined with the YOLO-based algorithm). As part of dol-sensors' protocol, unclear images due to dirt on the camera lens were discarded. If multiple pigs were detected in a frame, only the BW estimated for the pig closest to the RFID antenna (Farm 1: the pig with the head in the feeder; Farm 2: the pig with the head in the feeder partition) was maintained. If the closest pig to the antenna could not be determined, a dummy pig was recorded, and the respective sample was manually discarded. For selected segmented images, a regression neural network, developed and trained by dol-sensors, used available information in the image (e.g., head-to-tail distance, ribs' width, and ribs' curve) to estimate pig BW. Using the time stamps of the depth camera and RFID system, each measurement could be prescribed to an individual pig. If only an RFID reading or only a BW estimate was obtained, or if two pigs were registered to be in the feeding station (Farm 1) or in one feeder partition (Farm 2) simultaneously, the sample was discarded. The weight estimates of all the images (Table 1) of an individual pig taken on each day were used to calculate a median weight (i.e., the daily BW estimate, in kg). If a pig had <30 daily images, no individual BW estimate was calculated (Farm 1: all individual BW estimates were available; Farm 2: 1056 individual BW estimates (81%) were available). The pen estimated BW was calculated by taking the median of the weight estimates of all pictures of a particular pen. Image acquisition, segmentation and selection, weight estimation, and removal of outliers, if any, were conducted by dol-sensors using their confidential algorithm. Due to data storage malfunctioning, individual images and BW estimates from Farm 1 on the first weighing moment were not available and, hence, the Farm 1 analyses at individual level included the second and third weighing moments only.

2.3. Statistical analyses

Statistical analyses were performed for each farm separately in R v.4.1.1 [16]. The agreement between the estimated and scale-based BW was assessed at individual and pen level with repeated-measures concordance correlation coefficient (CCC) and repeated-measures Bland-Altman plot (library SimplyAgree v.0.0.2; [17]). Analyses at individual level were controlled for pen and pig, whereas analyses at pen level were controlled for pen. To assess the relationship between the number of daily images per pig on the BW estimation accuracy, we conducted a partial Pearson correlation ($r_{partial}$; library ppcor v.1.1; [18]) controlled for pig between the number of individual daily images and the BW estimation variation (scale-based BW minus estimated BW, in kg). Based on the criteria proposed by Hinkle et al. [19], CCC (range: 0–1) and r_{partial} (range: -1–1) values were interpreted as: negligible (0.0–0.3 and 0.0–-0.3), low (0.3–0.5 and -0.3–-0.5), moderate (0.5–0.7 and -0.5–-0.7), high (0.7–0.9 and -0.7–-0.9) or very high (0.9–1.0 and -0.9–-1.0). Based on the Bland-Altman plot reporting guidelines

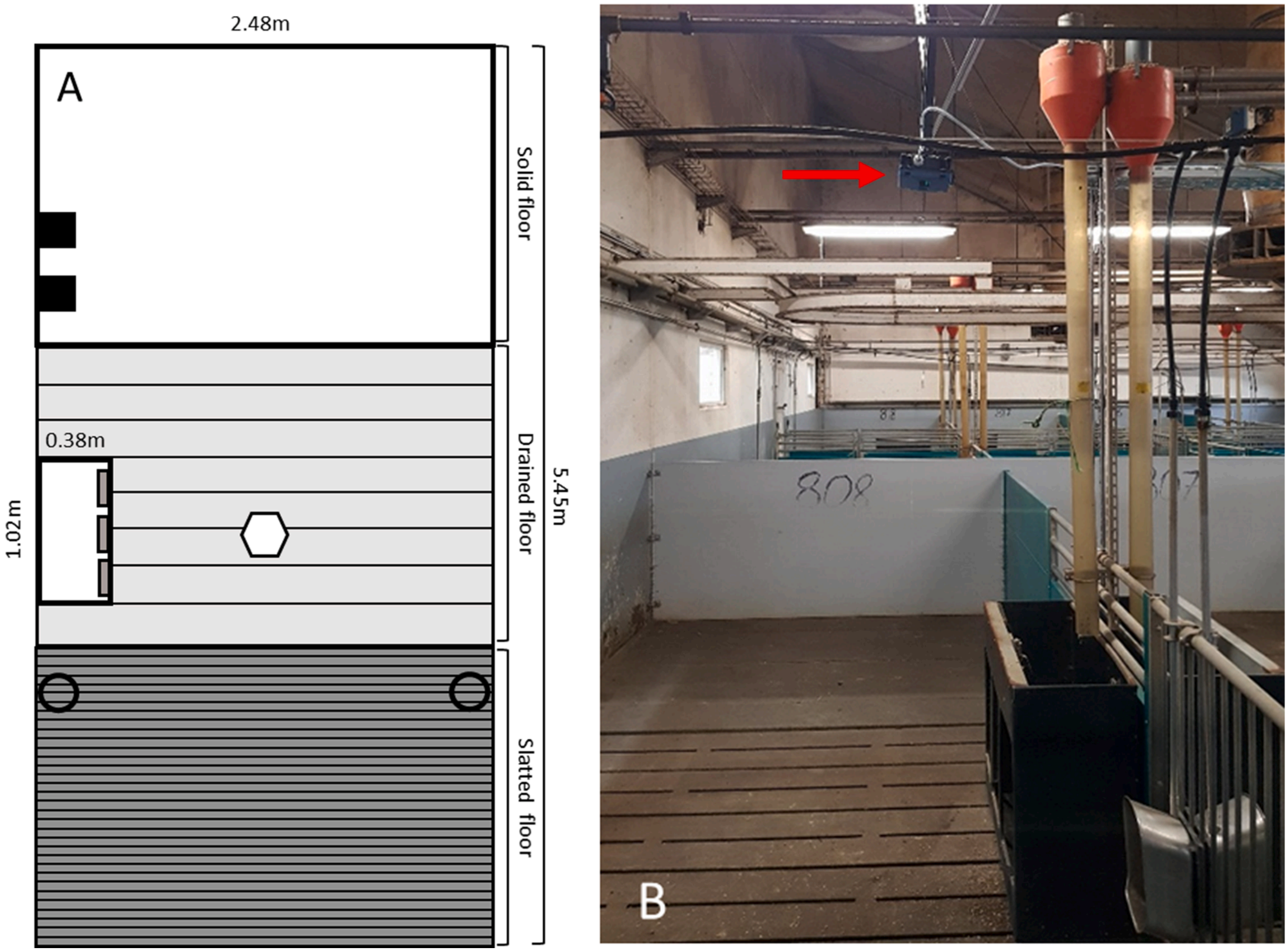

Fig. 2. (A) Illustration of the pen for fattening pigs on Farm 2. Feeders with three partitions are represented by the white rectangles, the iDOL65 3D camera by the white pentagon, drinking cups by the black hollow circles, and the two solid black squares represent two hard wooden sticks in separate vertical racks provided as general enrichment for all pens (retrieved from Larsen et al., 2018). (B) Illustration of the pen with the depth camera installed above the multi-partitioned feeder and indicated by the red arrow (credit: Guilherme A. Franchi).

proposed by Flegal et al. [20], a 95% Limits of Agreement (95%LoA) of 10% of the median scale-based BW [21] over the fattening period of each farm population (Farm 1: ±8.8 kg; Farm 2: ±5.5 kg) was pre-specified as an acceptable degree of agreement between the two measurements. The normal distribution of the number of individual daily images and BW estimation variation were graphically confirmed with a histogram and QQ-plot. The camera's BW estimation error (Root Mean Square Error; RMSE) at individual and pen level was assessed with mixed-effects linear regression (library glmmTMB v.1.1.2; [22]). The individual-level model included estimated BW as outcome variable, the scale-based BW, day and their 2-way interaction as fixed effects, number of daily images per pig as covariate, and pig nested in pen as random effect. The pen-level model included estimated BW as outcome variable, the scale-based BW, day and their 2-way interaction as fixed effects, and pen as random effect. We prespecified an RMSE ≤5% as acceptable [11]. Model assumptions of normality and heteroscedasticity were confirmed through graphical inspection of the residuals.

3. Results and discussion

On Farm 1, the agreement between the individual estimated BW and the individual scale-based BW was very high at individual (CCC: 0.97; 95%Confidence Interval (CI): 0.963–0.971) and pen (CCC: 0.99; 95%CI: 0.989–0.995) level. The BW was overestimated by the 3D camera in comparison with the scale with a mean difference of 1.5 kg at both individual (95%LoA=-9.5–6.5 kg) and pen level (95%LoA=-8.5–5.5 kg) (Fig 3). The relationship between number of images and BW estimation accuracy was negligible ($r_{partial}$=-0.20; N=204 observations; P-value=0.004). The RMSE were 1.7% (1.5 kg; R^2=0.98) and 2.4% (1.8 kg; R^2=0.99) of the median weight over weighing moments at individual and pen level, respectively.

On Farm 2, the agreement between the individual estimated BW and the individual scale-based BW was also very high at individual (CCC: 0.98; 95%CI: 0.978–0.982) and pen (CCC: 0.98; 95%CI: 0.974–0.984) level. At individual level, the BW was overestimated by the 3D camera in comparison with the scale with a mean difference of 0.2 kg (95%LoA=-6.9–7.4 kg) (Fig 3). At pen level, the BW was underestimated by the 3D camera in comparison with the scale with a mean difference of 1.5 kg (95%LoA=-8.9–6.0 kg) (Fig 3). The relationship between the number of images and BW estimation accuracy was negligible ($r_{partial}$=-0.08; N=1056 observations; P-value=0.014). The RMSE were 3.6% (1.9 kg; R^2=0.98) and 3.1% (1.7 kg; R^2=0.98) of the median weight over weighing moments at individual and pen level, respectively.

On both farms, based on the CCC and RMSE outcomes, the performance of the depth camera and its underlying algorithm was satisfactory at both individual and pen level, and better than the BW estimation reported in earlier studies using other types of depth cameras. For instance, Kongsro [13] and Condotta et al. [4], using a Microsoft Kinect camera, reported similar R^2 (0.99) compared with our results. However, they found higher RMSE ([13]: 3.4 kg, 4.8%; [4]: 3.0 kg, 4.9%) than our

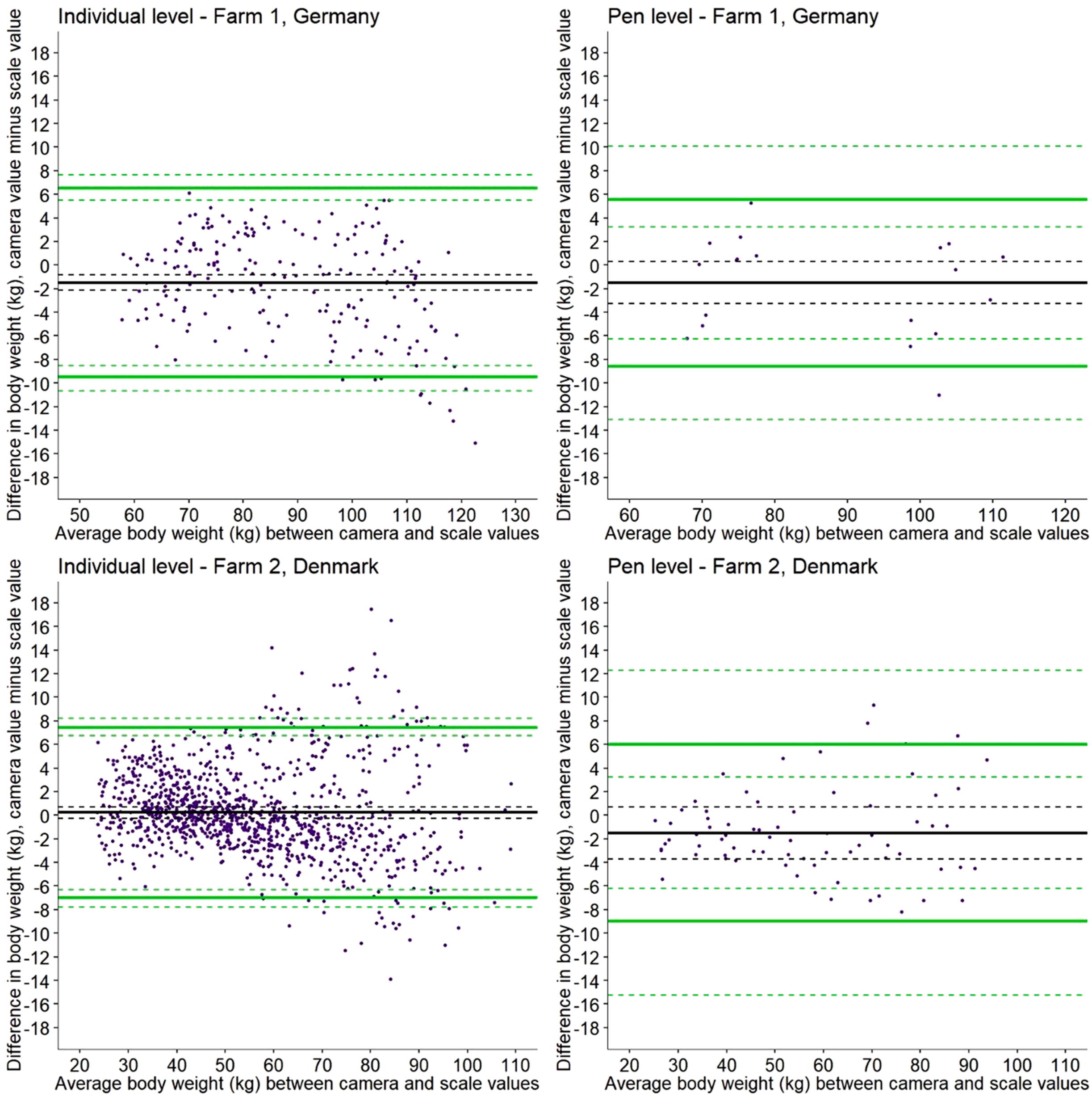

Fig. 3. Bland-Altman plots of paired differences between camera and scale BW values against the average of the pairs of methods at individual and pen level on Farms 1 and 2. In each plot, the solid black line indicates the mean difference, the black dashed lines indicate the mean difference's 95% confidence interval, the green solid lines indicate the upper and lower limits of agreement (LoA), and the green dashed lines indicate the LoA's 95% confidence intervals. The purple dots indicate individual pigs on the individual-level plots and individual pens on the pen-level plots.

study. In Kongrso [13], 71 finisher pigs (37 Duroc, 34 Landrace) with a BW range of 29–139 kg were used, whereas Condotta et al. [4] used 234 finisher pigs (78 Landrace, 78 Duroc, and 78 Yorkshire) sampled at four different moments (BW range: 15–110 kg). Additionally, using a second version of the Microsoft Kinetic camera and finisher pigs (unknown breed) with an average BW of 120 kg, Fernandes et al. [14] reported an R^2 of 0.88 and an RMSE of 4.4 kg (3.6%), both values poorer than the ones reported herein. Overall, the iDOL65 camera revealed a satisfactory BW estimation performance over farms and development stages, overcoming breed differences that could potentially reflect in differences in body conformity and, consequently, influence BW estimation [1]. Furthermore, the negligible correlation between the number of individual daily images and individual BW estimation accuracy on both farms indicates the camera satisfactorily estimated pigs' BW regardless of the amount of individual daily images available. This is particularly relevant for subordinate pigs who may show a reduced daily feeder visit frequency [23]. Moreover, the camera performed well across two different feeding site set-ups with minimum physical disturbance of the pen layout, except for minor adaptations such as installation of a rack above the feeder to mount the camera and removal of feeding station' top fence to ensure pigs' body were visible on Farm 1 (Fig. 1) and a metal rod to hold the camera at the required position and height on Farm 2 (Fig. 2).

Yet, the overall performance of the iDOL65 on Farm 1 was better than on Farm 2. We propose two explanations for such a difference. First, the more frequent lens cleaning and camera calibration may have benefited the iDOL65's BW estimation performance on Farm 1. Had the cameras on Farm 2 been inspected during the experimental period, potential sources of error compromising high-quality image acquisition might have been avoided and a greater BW estimation performance might have been achieved. Second, on Farm 2, several animals were removed from pens due to sickness from the seventh recording day. Such a disturbance on the social environment likely disturbed the hierarchy and the individual access to resources such as the feeding site. Consequently, image sampling and BW estimation, particularly at individual level, may have been compromised [24].

Except for the pen-level outcomes on Farm 1, the 95%LoA outcomes were outside the respective prespecified acceptable ranges. Moreover, our Bland-Altman plots revealed few points of disagreement (i.e., purple points outside the LoA in Fig. 3) between the individual estimated BW and the individual scale-based BW on Farm 1 when pigs weighed >110 kg and several points of disagreement on Farm 2 when pigs weighed between 60–90 kg. According to the manufacturer, the dataset used to train and test the iDOL65's algorithm included mostly pigs weighing between 15–110 kg, and few pigs with BW outside this range. Hence, this can explain the BW estimation disagreement cases observed on Farm 1. For the disagreement cases observed on Farm 2, we propose two connected justifications. When pigs reach approximately 60 kg, they are typically subjected to a dietary change to meet their increasing nutrient requirements [25], which, in combination with differences in pig size and stocking density, can lead to increased competition for access to the feeder [23]. Consequently, as multiple pigs could have tried to access the same feeder partition, the camera may have had issues to take images of the actual eating pig (closest to the RFID antenna) and detect the respective pig body boundary without the presence of another pig's body part. This may also explain the absence of BW estimates of some pigs on Farm 2. Such a challenge was reported by Buayai et al. [26] using a semi-automatic machine vision approach in commercial finisher pigs whose 2D images were also taken from the top view of the feeder. Due to the algorithm confidentiality, we were unable to examine in detail the aspects resulting in reduced BW estimation accuracy at individual level.

In conclusion, the iDOL65 showed a satisfactory BW estimation performance at both individual and, especially, pen level over different development stages, feeding site set-ups and breeds. The minimal physical interventions needed to install the camera system above the feeding site and no need for habituation period for the animals or handling by the barn staff represent an advancement in 3D camera technology and a potential solution for BW estimation in commercial farms. We encourage further camera performance optimisation, particularly for individual-level BW estimation, by inclusion of BW observations over 110 kg in the algorithm's training and testing and experimentation of the camera under other pen and feeding site layouts. Additionally, to encourage the iDOL65 adoption by farmers, we suggest an integration of the camera system with equipment (e.g., robots, drones) allowing for moving the camera across the pen, or even across the pig unit section, and taking images of animals at any time and location. This improvement can potentially permit BW estimation at individual level independent of a combination with an RFID system installed at the feeding site, which is not commercially available yet.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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