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Effect of two different feeding strategies on energy intake from pasture, feed efficiency and growth performance of growing-finishing pigs in a mobile pasture system

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HIGHLIGHTS

- High concentrate inputs constitute an environmental challenge in free-range pig production.
- The potential to obtain compensatory growth was evaluated for growing-finishing pigs in a mobile pasture system.
- Compensatory growth was partially achieved.
- High daily gains and feed efficiencies were found across feeding regimes.
- Pigs were able to cover a substantial share of their daily energy requirements from direct foraging.

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ABSTRACT

Free-range rearing allows pigs to perform species-specific and normal behavior, and is an important welfare attraction among consumers, but high inputs of concentrate challenge the sustainability of this practice. Exposing pigs to limited access to concentrate followed by ad libitum feeding could reduce feed input while improving average daily gain and feed conversion ratio. The objective of the study was to investigate the effects of restricted feeding in the grower phase followed by ad libitum feeding in the finisher phase on growth performance, feed efficiency and intakes from concentrate and the range area in a rotational pasture system. A total of 64 pigs with a mean live weight (LW) of 30 kg (SD 3.9) and an average age of 69 days were randomly assigned to one of two feeding strategies; AL (ad libitum from 30 kg LW to slaughter) or RES-AL (restricted feeding supplying 95–67% of recommended supply from 30 kg to 70 kg followed by ad libitum feeding until slaughter). Slaughter of RES-AL pigs was performed after 84 days, while AL pigs were slaughtered after 76 days. Access to new pasture area was provided twice a week throughout the experiment using mobile paddocks. Results showed that RES-AL pigs partially achieved compensatory growth as their growth rate was numerically greater (71 g/d) than for AL pigs during realimentation from 70 kg to slaughter (1419 vs. 1348 g/d). Daily growth rates from 30 kg to slaughter were high across feeding strategies, 1051 g vs. 1139 g for RES-AL and AL, respectively ($P < .001$). Concentrate feed conversion efficiencies were also high, 34.2 MJ ME/kg LW gain for RES-AL pigs and 34.5 MJ ME/kg LW gain for AL pigs ($P > 0.05$). It was estimated that RES-AL pigs covered 25% of daily energy requirements from direct foraging during restricted period and 10% during realimentation. For comparison on the corresponding periods, AL pigs covered 14% and 6%, respectively. Findings indicate a great potential for high growth rates and high feed efficiencies under free-range conditions as well as substantial energy inputs from direct foraging, most pronounced during concentrate restriction. Due to the lack of improved feed efficiency for RES-AL pigs compared with AL pigs, the sustainability was not improved in free-range reared pigs when focusing on concentrate input exclusively.

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1. Introduction

Free-range production of fattening pigs is considered animal friendly because pigs are allowed natural behavior such as exploration and foraging. From an environmental perspective, free-range systems are challenged by high risk of soil nutrient losses largely caused by extensive nutrient inputs from high concentrate consumption (Eriksen et al., 2006a; 2006b). Earlier studies have addressed this problem by investigating the effect of restrictive feeding combined with access to attractive foraging crops. Even with significant contributions to daily energy and nutrient intake from direct foraging in these studies, restrictive feeding throughout the growing-finishing period caused impaired daily growth (Kongsted et al., 2013; Jakobsen et al., 2015) and meat quality (Kongsted and Therkildsen, 2014). This is not desirable from a production perspective and the strategy should be revised to achieve reduced concentrate consumption and acceptable growth rates.

Compensatory growth is a well-known process in which an animal after a period of moderate nutritional deficit achieves catch-up growth in a subsequent period with higher feed intake. Such feeding strategies have been studied in indoor conventional pigs with varying results (Fabian et al., 2004; Fernández and Nørgaard, 2009), but with examples of increased feed efficiency and compensatory growth potential (Oksbjerg and Therkildsen, 2007; Therkildsen et al., 2004). A similar feeding strategy has not been tested on free-range pigs. Unlike indoor pigs, free-range pigs have the opportunity to supplement concentrate feed with significant amounts of nutrients and energy through foraging (Kongsted et al., 2013; Jakobsen et al., 2015). Especially, energy intake from rooting and grazing becomes interesting in free-range systems, where controlled feeding of concentrate is difficult due to relatively higher and more varying energy requirements as a consequence of weather conditions and locomotive activity combined with energy contributions from the range area (Eskildsen et al., 2020a; 2020b). Pasture access could thus be advantageous in a compensatory growth process and potentially contribute positively to cover the daily energy requirements of free-range pigs.

Continuous allocation of new pasture area is expected to increase intake from foraging since pigs by nature are investigating new food areas (Wood-Gush et al., 1990), and prefer grazing on new allotted areas (Stern and Andresen, 2003; Rivero et al., 2017). Additional advantages of paddock mobility can be faster recovery time of damaged pasture (Kelly et al., 2002) and a more even distribution of manure (Eriksen and Kristensen, 2001) reducing risk of soil nutrient losses. From those perspectives, mobile concepts have great potentials to maximize nutritional contributions from direct foraging and mitigate environmental challenges.

The overall objective in the present study was to investigate the effect of restricted concentrate feeding in the grower phase followed by ad libitum feeding in the finisher phase on growth performance, feed efficiency, and energy intakes from the pasture in a mobile system. It was hypothesized that pigs fed concentrate restrictedly in the grower phase would be able to achieve compensatory growth by the time of slaughter and improve feed efficiency of concentrate compared with pigs fed concentrate ad libitum throughout the growing-finishing period.

2. Materials and methods

2.1. Experimental site and animals

The experiment was carried out at Aarhus University Research unit Foulum, Denmark (56° 9′ 17″ North, 9° 34′ 58″ East) from July 25 until October 17 2017. Soil conditions are predominantly loamy sand. Climate data were extracted from a national climate station registering hourly air temperature at a location 1.7 km from the experimental site.

A total of 64 pigs, with an average weight of 30 kg (SD 3.9) and an average age of 69 days were included in the experiment. Of these, 32 castrated male and female littermates genetically originated from Topigs Norsvin TN70 sired by Danbred Duroc (TN) and 32 castrated male and female littermates from Danbred Landrace x Yorkshire sired by Danbred Duroc (LY). There was an equal number of male and female pigs. All pigs were born and reared free-range at Aarhus University, and exposed to comparable conditions including ad libitum feeding from weaning to experiment initiation. The pigs were not snout ringed.

2.2. Feeding strategies

The experimental period was divided into two periods; a grower phase from 30 kg to ~70 kg (day 1 to 51; period 1) and a finisher phase from ~70 kg until slaughter (day 51 to slaughter; period 2).

Within each sex and genotype, the 64 pigs were stratified for live weight (LW) within four blocks, where pigs were allocated to one of two experimental feeding strategies by sex, genetics, and weight (stratified randomization). Pigs exposed to strategy 1 were fed concentrate ad libitum throughout period 1 and 2 (AL). Pigs exposed to strategy 2 were fed restrictedly during period 1 and ad libitum during period 2 (RES-AL).

All pigs received 20 MJ Metabolizable Energy (ME) of concentrate/individual on experiment day 1, corresponding to 115% of Danish energy recommendations for indoor pigs (Anonymous, 2005). Edwards (2003) estimated an increase of approximately 15% in daily energy requirements for pigs reared free-range in Northern European countries, attributed to climatic related energy demand and locomotive activity. An estimate supported in a recent study by Eskildsen et al. (2020b). The initial concentrate level was adjusted accordingly. Feed residues from the previous day were collected prior to daily feeding to determine concentrate intake on a daily basis on a pen level. In the absence of residues, the feed level was increased. For AL pigs, the increase continued throughout the experimental period. For RES-AL pigs, the severity of restriction and length of the realimentation period (period 2) was based on Oksbjerg and Therkildsen (2007). The daily concentrate supply stagnated at 26 MJ ME on day 10 in period 1, corresponding to 95% of recommendations in the beginning of the 50 day restriction period and decreased to 67% of recommendations at the end of the restriction period. In period 2, RES-AL pigs had ad libitum access to concentrate after four days of adaptation from day 49 to day 52. Ad libitum fed pigs were fed in closed feed troughs whereas pigs fed restrictedly were fed in open feed troughs to ensure that all pigs had equally access to the concentrate.

Concentrate was supplied to all animals daily at 8 AM. Conventional standard compound feeds for grower (period 1) and finisher pigs (period 2) were used for all experimental pigs (Table 1). The concentrate composition followed the nutrient recommendations for conventionally housed pigs (Tybirk et al., 2015).

Table 1
Dietary composition in percentage of diets and chemical composition of grower and finisher diet.

Item	Grower diet	Finisher diet
Ingredients, [%]		
Dry matter	87.3	87.5
Barley	38.8	30
Wheat	29.9	29.9
Soybean cake	16.8	18.5
Rye	5	12
Oat	-	4
Bran	3.5	1.5
Dried beet pulp	2	-
Palm fat	0.9	0.9
Minerals and feed additives	2.63	2.67
Chemical composition		
Crude protein, %	14.7	14.7
Lysine, g/kg	9.0	9.0
Methionine, g/kg	2.7	2.6
MJ ME/kg	12.6	12.6

2.3. Pasture, paddocks and grazing design

Eight experimental paddocks were located consecutively in a block design consisting of two paddocks within each of four blocks. Each paddock was provided with an insulated hut of 11.3 m^2 with straw bedding and a wallowing area when daily temperature exceeded 15C. There were eight pigs in each paddock. The forage crop consisted of a ryegrass (65%), red fescue (25%), and white clover (10%) seed mixture sown in spring 2016. Forage crop was cut to approximately 5 cm height 13 days before the experiment was initiated. No fertilizer or pesticides were applied.

The grazing design was a combination between strip grazing to allocate new fresh pasture, and movement of huts and rear fence to avoid activity in the old pasture and thus increase the possibility of pasture regrowth. This design was similar for all paddocks. Front fence was moved twice every week to allow access to new pasture. Rear fence was moved four times during the experimental period along with huts and feeding areas. Huts were placed in the old grazing area to avoid occupation of area with fresh pasture.

Due to distinct slaughter dates, the total area used throughout the experimental period was 300 m^2 for a RES-AL pig, and 275 m^2 for an AL pig. Divided into periods, the daily paddock area/pig was 3.5 m^2 in period 1, and 3.6 m^2 and 3.7 m^2 for RES-AL pigs and AL pigs in period 2, respectively. The daily paddock area varied because of the different frequency in movement of front and rear fence. While movement of front fence increased the available area, movement of rear fence reduced the available area/pig but increased the share of fresh pasture markedly.

2.4. Recordings

All pigs were weighted individually before experiment initiation, at day 51 (before transition from restrictive feeding to ad libitum for RES-AL pigs), and at slaughter. Slaughter was planned at an average LW of approximately 115 kg for both feeding strategies. Control weighing of selected pigs were performed during the experimental period to achieve similar average weights at slaughter. Due to slower growth, the RES-AL were slaughtered eight days later than AL pigs (day 84 compared to day 76 for AL pigs).

Crop samples were collected in all paddocks prior to grazing in a diagonal pattern across the paddock in the subsequent section three- and six meters from the rear fence. Samples were collected six times during the experiment from two 0.25 m^2 squares harvested at 2-centimeter height to quantify herbage dry matter (DM) mass and quality. On each collection day, samples within RES-AL paddocks and AL paddocks, respectively, were mixed and analyzed as single aggregate samples.

2.5. Energy calculations

Total energy requirements were calculated as the sum of energy required for maintenance, growth, and additional heat associated with growth, thermoregulation and locomotive activity (Theil et al., 2020). Energy intakes from foraging in the range area were estimated by subtracting the contributions from concentrate intakes from total daily energy requirements.

Maintenance. Daily ME requirement for maintenance (MEm) was calculated according to NRC (2012) for pigs within 20-100 kg LW:

$$ME_m, kJ/day = 444 \times LW(kg)^{0.75} \quad (1)$$

Retained energy. Energy requirement for growth was estimated as energy retained in protein (RPE) and energy retained in fat (RFE) in period 1 and period 2, respectively. Daily protein and fat retention rates were calculated from estimates of body protein and body concentration (%) of the empty body weight from 25 to 150 kg predicted from LW for gilts and barrows using the following equations (Danfær and Strathe, 2012):

$$\text{Body protein}_{gilts}, \% = 0.0005xLW(kg)^2 + 0.0909xLW(kg) + 16.393 \quad (2)$$

$$\text{Body protein}_{barrows}, \% = 0.0005xLW(kg)^2 + 0.1002xLW(kg) + 15.378 \quad (3)$$

$$\text{Body fat}_{gilts}, \% = 0.0004xLW(kg)^2 + 0.1949xLW(kg) + 3.7351 \quad (4)$$

$$\text{Body fat}_{barrows}, \% = 0.0004xLW(kg)^2 + 0.2195xLW(kg) + 3.2241 \quad (5)$$

The protein and fat pools at start and end of each period was calculated as follows:

$$\text{Protein pool}\,(kg) = LW(kg) \times \text{body protein}, \%/100 \quad (6)$$

$$\text{Fat pool (kg)} = LW(\text{kg}) \times \text{fat protein}, \%/100 \quad (7)$$

Finally, protein and fat pools were calculated as follows:

$$\text{Protein deposition},\ g/d = (\text{Protein pool}_{end} - \text{Protein pool}_{start})/(days) \times 1000g/kg \quad (8)$$

$$\text{Fat deposition}, g/d = (\text{Fat pool}_{end} - \text{Fat pool}_{start})/(days) \times 1000\,g/kg \quad (9)$$

Weighed averages of body shares of protein and fat for gilts and barrows were used to take into account sex variation. The protein deposition (PD) and fat deposition (FD) served as a basis for calculation of a representative share of protein and fat in period 1 and period 2 based on the pigs' LW at experiment initiation, LW at the end of period 1 and LW at the end of period 2. Energy contents of 1 g protein (23.9 kJ) and 1 g fat (39.8 kJ) were used to calculate daily RPE and RFE (Theil et al., 2020).

Heat production due to retained protein and fat. Heat production associated with RPE and RFE retention was estimated by assuming a partial energetic efficiency of 60% for protein and 80% for fat (Danfær and Strathe, 2012).

Heat production due to thermoregulation. The energy requirement for cold thermogenesis was set to 17 kJ ME/ LW ($kg^{0.75}$)/day/C below the lower critical temperature (LCT) (Close and Poornan, 1993). Average daily temperatures (7 a.m. to 7 p.m.) were calculated for period 1 and period 2, respectively. Daily energy requirement for thermoregulation (t) was calculated as:

$$E_{thermo}, kJ/day = 17\,kJ\,ME \times LW(kg)^{0.75} \times {}^{\circ}\text{C below LCT} \quad (10)$$

Daily average temperatures for period 1 and period 2 were assumed to present a valid basis for estimating energy for thermoregulation because there was only few cases of hourly temperatures throughout both periods that exceeded LCT. Temperature in the hut is unknown and not included in the estimations.

Heat production due to locomotive activity. Daily energy requirement for locomotive activity was calculated as the sum of requirements for standing and walking. Since no data are available on energy requirements for grazing and rooting behavior in growing-finishing pigs in free-range systems, the sum of requirements for standing and walking was multiplied by a factor 2.5 based on earlier results on heat production from physical activity in pigs in Jakobsen et al. (1994).

Energy for standing activity was defined as 0.273 kJ ME/kg metabolic LW ($kg^{0.75}$)/minute as reported for sows by Noblet et al. (1993).

Requirements for walking in level surface areas were defined as 0.003 kJ NE/kg LW/meter walked (Lachica et al., 1997; Rodriguez-Estevez et al., 2010).

Total energy requirement. The total energy requirement (output of energy) was estimated by summing up retained energy (as protein and fat) and heat produced due to maintenance, locomotive activity, thermoregulation, and retention of fat and protein. Estimations of energy requirements for maintenance, thermoregulation, and activity were based on the median LW of pigs from each feeding strategy within each period, *i.e.*50 kg and 94 kg for RES-AL pigs in period 1 and period 2, respectively, and 56 kg and 99.5 kg for AL pigs in period 1 and period 2, respectively (Fig. 3). Energy requirement for growth (protein and fat retention) was calculated by mean LW within the intervals in period 1 (RES-AL = 30–70 kg and AL = 30–82 kg) and in period 2 (RES-AL 70–118 kg and AL = 82–117 kg) for distinct feeding strategies.

2.6. Calculations and statistical analysis

The effects of feeding strategy, genotype and sex on LW (day 1, day 51 and at slaughter), average daily gain (day 1–51, day 51 to slaughter and day 1 to slaughter), lean meat percentage and back fat were investigated by the following mixed model using the MIXED procedure in SAS (Littell et al., 1996):

(1) $Y_{ijkl} = \mu + \alpha_i + \beta_j + \lambda_k + \gamma_l + \delta w_{ijkl}\, \alpha\beta_{ij} + \alpha\lambda_{ik} + \beta\lambda_{jk} + \alpha\beta\lambda_{ijk} + A_{ik} + E_{ijkl}$, where Y_{ijkl} is the observation for the individual pig (daily gain, lean meat percentage, back fat), μ is the overall mean, α_i is the effect of feeding strategy (i= AL, RES-AL), β_j is the effect of genotype (j= LY, TN), λ_k is the effect of sex (k= female, castrated male pigs), γ_l is the effect of block (l= 1–4), w_{ijkl} is the initial LW and δ the corresponding regression parameter, A_{ik} is the normally distributed random effect of group (i= AL, RES-AL) within block (l= 1–4). E_{ijkl} was assumed to be normally distributed where observations from different groups were assumed to be independent while observations for the same group were assumed to be correlated. All two and three-way interactions between feeding strategy, genotype and sex were included ($\alpha\beta_{ij}$, $\alpha\lambda_{ik}$, $\beta\lambda_{jk}$, $\alpha\beta\lambda_{ijk}$). All interactions and main effects with significance level above 0.1 were removed from the model one by one and the analysis was repeated. When investigating the effects of feeding strategy, genotype and sex on daily gain day 1–51, initial LW and LW on day 51 was included as a covariate. Feed conversion ratio (FCR) was investigated at group level (group level, $n = 8$), based on concentrate intake, with a model including feeding strategy and block only.

3. Results

3.1. Climatic conditions

The average outdoor diurnal temperature throughout the trial (July to September) was 13.1 °C, ranging from 7.4 °C to 21.5 °C. The daily average between 7 a.m. and 7 p.m. was 16.3 °C in period 1 and 12.9 °C in period 2. Total rainfall was 287 mm throughout the experiment, and the diurnal average wind speed was 3.2 m/s with minimum and maximum daily averages of 0.9 m/s and 6.3 m/s, respectively.

Analysis of crop samples showed variation in DM content across the experimental period with highest DM in August, 21.0% (Table 2). Dry matter content was 18.8% in July and 15.5% in September. Crude protein (CP) was highest in July (19.4% of DM), but lower in August (17.5% of DM) and September (18.5% of DM).

3.2. Feed intake, growth performance, feed efficiency, and lean meat percentage

Daily concentrate intake was constant through most of period 1 for RES-AL pigs (Fig. 1) with an average of 25 MJ ME/d (Table 3). On average, AL pigs ingested 28% more concentrate per day compared with RES-AL pigs in period 1. Pigs exposed to restriction increased their daily concentrate intake to the level of AL pigs within a few days after transition from restrictive to ad libitum feeding, and had a 3% lower average daily feed intake (ADFI) than AL pigs in period 2. As expected, AL pigs increased their daily intake steadily throughout the experimental periods. Overall, AL pigs had a daily concentrate intake which was 10% higher than RES-AL pigs (39.3 MJ ME/d vs. 35.9 MJ ME/d).

Table 2
Nutrient content of forage crop in percentage of dry matter (DM), energy content of forage crop and herbage availability in kg dry matter per hectare.

Item	Season July (day 3)	August (day 30)	September (day 57)
DM, %	18.8	21.0	15.5
Crude protein	19.4	17.5	18.5
Crude fat	3.5	4.0	4.5
Ash	8.3	8.6	8.6
MJ ME/kg DM	6.2	6.4	6.9
Herbage availability, kg DM ha^{-1}	993	1021	1430

Restricted feeding in period 1 caused a 22% decline in average daily gain (ADG) for RES-AL pigs as compared with AL pigs ($P < .0001$; Table 3). The lower daily growth rate reduced LW on day 51, which was 15% lower than that observed for AL pigs. The FCR was, however, comparable between the two feeding strategies for period 1. Neither genotype nor sex affected ADG. During period 2, RES-AL pigs increased their daily gain by 5% above the level observed for AL pigs and showed improved FCR numerically. Overall, RES-AL pigs had a significant lower ADG compared with AL pigs corresponding to 8% throughout the experimental period, while pigs had comparable FCR in the two feeding strategies. No significant two- or three-way interactions were found for any traits.

Fig. 2 illustrates a clear clustering of ADG for the two feeding strategies in period 1 despite a large variation between individuals. Generally, restrictedly fed pigs were clearly growth retarded during period 1 compared with AL pigs, while period 2 showed growth rates of comparable magnitude. It is also clear, that there was a large variation between individuals, indicating that pigs responded differently to apparently similar rearing conditions. Deviations among individuals were numerically greater between AL pigs, and especially three AL pigs seemed to affect the ADG negatively in period 2.

No effect of feeding strategy was found on lean meat percentage or back fat thickness (Table 3). Breed and sex affected lean meat percentage and back fat ($P < .0001$). The lean meat percentage and back fat was 5% higher and 2.4 mm lower, respectively, for TN pigs compared to LY pigs. Concomitantly, the lean meat percentage and back fat was 5% higher and 2 mm lower for female pigs compared with male pigs. No health problems were observed in the animals during the experiment.

3.3. Energy intakes from the range area

Estimates of energy requirements for maintenance, growth, thermoregulation and locomotive activity are presented in Fig. 3. Across feeding strategies, pigs covered a considerable part of their daily energy requirements from foraging in the range area, especially in period 1 corresponding to 25% and 14% for RES-AL and AL pigs, respectively. In period 1, the estimated daily energy requirement of RES-AL pigs was 11% lower than AL pigs, while they had a 23% lower daily intake of concentrate compared with AL pigs.

The slightly lower maintenance requirements for RES-AL pigs were attributed to the lower median weights for RES-AL pigs compared to AL pigs (50 kg LW vs. 56 kg LW in period 1 and 94 kg LW vs. 99.5 kg LW in period 2). The retarded growth in RES-AL pigs during period 1 caused a 27% lower energy requirement for growth than AL pigs. In period 2, energy requirements for growth were comparable. Energy requirements for thermoregulation were found similar between feeding strategies as dependent on LCT and temperature.

Energy requirements for locomotive activity were 35% higher for RES-AL in period 1 due to a significantly higher activity level and an assumed longer distance walked. Estimations were based on energy for standing and energy for walking. Preliminary results from behavioral observations in the present experiment conducted on day 42 to 45 (period 1) and on day 70 to 73 (period 2), showed that RES-AL pigs were active 48% of the day in period 1 and 32% percent of the day in period 2 (unpublished data). The proportion of activity was an aggregation of observed rooting, grazing, standing and walking, and eating concentrate behavior. A daily observation time of approximately 12 h (from sunrise

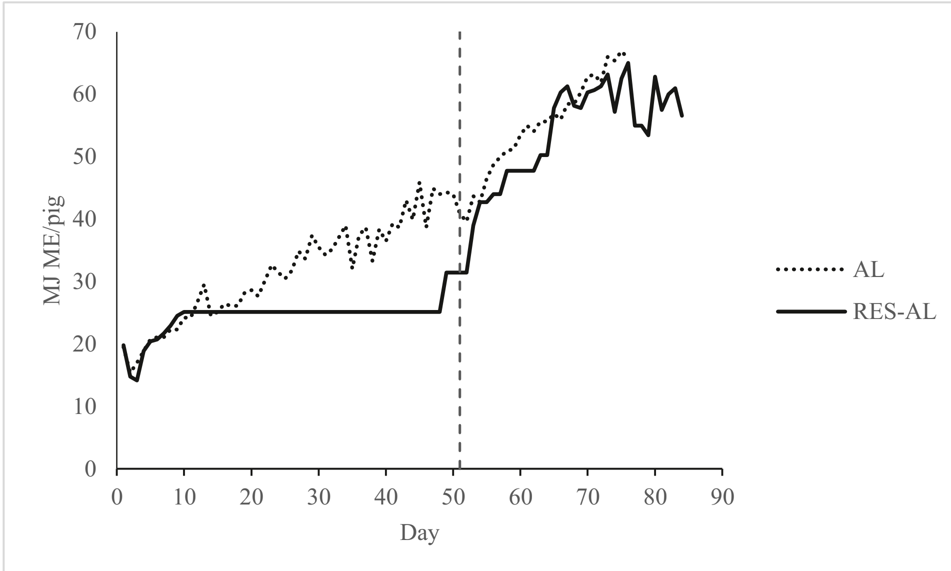

Fig. 1. Daily concentrate intake from day 1 until slaughter, MJ ME per pig.

Table 3
LS-means, effect of feeding strategy, genotype and sex on weight, average daily gain (ADG), average daily feed intake (ADFI), feed conversion ratio (FCR), lean meat percentage and back fat thickness.

	Feeding strategy		Genotype		Gender		Level of significance[1]		
	RES-AL	AL	LY	TN	Female	Castrated male	Feeding strategy	Genotype	Sex
No. of animals	32	32	32	32	32	32			
Period 1 (day 1 – 51)									
LW day 1, kg	30	30	29	31	30	30	NS	0.01	NS
ADG, g/pig	801	1031	926	905	908	924	<.0001	NS	NS
ADFI, MJ ME/pig	25.0	32.1	-	-	-	-	<.01	-	-
FCR, MJ ME/kg LWgain	31.2	31.1	-	-	-	-	NS	-	-
Period 2 (51 – slaughter)									
LW day 51, kg	70	82	74	77	75	76	<.001	NS	NS
ADG, g/pig	1419	1348	1403	1363	1356	1410	NS	NS	NS
ADFI, MJ ME/pig	51.9	53.3	-	-	-	-	NS	-	-
FCR, MJ ME/kg LW gain	36.6	39.7	-	-	-	-	NS	-	-
Period 1+2 (day 1 – slaughter)									
LW at slaughter, kg	118	117	-	-	-	-	NS	-	-
ADG, g/pig	1051	1139	1110	1080	1081	1109	<.001	NS	NS
ADFI, MJ ME/pig	35.9	39.3	-	-	-	-	<.01	-	-
FCR, MJ ME/kg LW gain	34.2	34.5	-	-	-	-	NS	-	-
Days in experiment	84	76	-	-	-	-	-	-	-
Lean meat percentage	60.3	60.7	58.9	62.1	61.9	59.1	NS	<.0001	<.0001
Back fat, mm	13.7	13.4	14.8	12.4	12.6	14.6	NS	<.0001	<.0001

[1] *P*-values below 0.05 indicate a significant effect. No two or three interaction effects were found.

to sunset) suggests that RES-AL pigs were in a standing position (regardless of activity) for 345 min and 228 min in period 1 and 2, respectively. Similar estimates for AL pigs corresponded to 218 min (*i.e.* they were physically active 30% of the day) and 199 min (physical active 28% of the day) in period 1 and 2, respectively. On day 51, at weighing, an activity meter was placed on two pigs from each of the feeding strategies to measure distance walked within a battery time of approximately 7.5 h. Within this period, pigs walked in average 2.0 km. Considering that growing pigs are more active than finisher pigs, the daily distance walked was assumed to be 3 km for AL pigs and 4 km for RES-AL pigs during period 1, and 2 km for both AL and RES-AL pigs in period 2, where both groups were fed ad libitum. The distance for RES-AL pigs in period 1 was set to be higher because they were active in a greater part of the day.

4. Discussion

4.1. Growth performance and feed efficiency

Despite an increased ADG during period 2, RES-AL pigs needed eight days more than AL pigs to reach similar weight at slaughter. Overall ADG from 30 kg LW to slaughter was high for both treatments (1051 g/day for RES-AL and 1139 g/day for AL pigs). Results correspond well with findings in a similar experimential setup with ad libitum feeding and Jerusalem artichokes as foraging crop by Kongsted et al. (2013), while being markedly higher compared with results by Fernández and Nørgaard (2009), who investigated compensatory growth response in organic indoor growing-finishing pigs, with access to a partially covered outdoor concrete area. In that study, pigs exposed to the compensatory growth feeding strategy received 70% of expected concentrate consumption and duration of realimentation was 57 days, *i.e.* clearly longer than in the present study with a 34 day long realimentation period. Despite the long realimentation in Fernández and Nørgaard (2009),

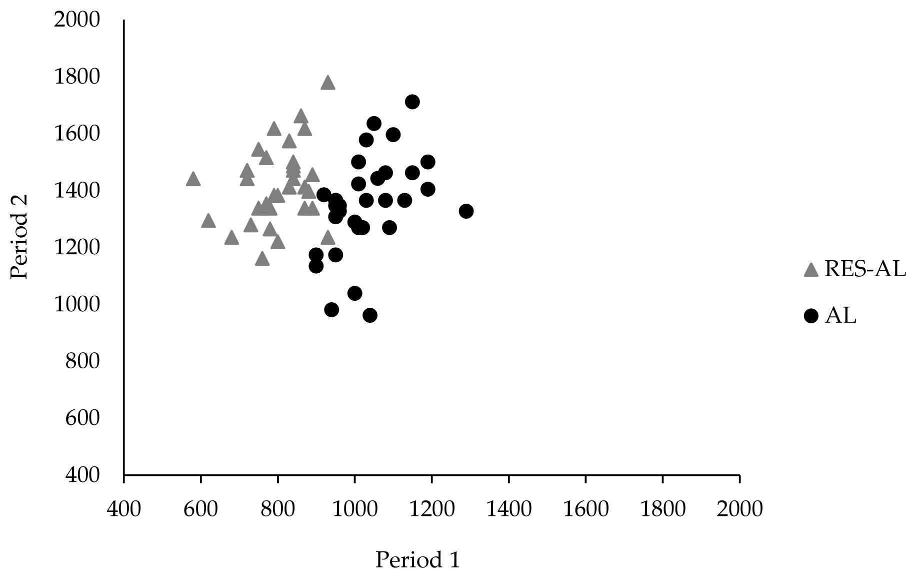

Fig. 2. Relation between daily growth rates observed for individual pigs fed one of two different feeding strategies (RES-AL pigs were fed restricted in period 1 and ad libitum in period 2, AL pigs were fed ad libitum in period 1 and period 2).

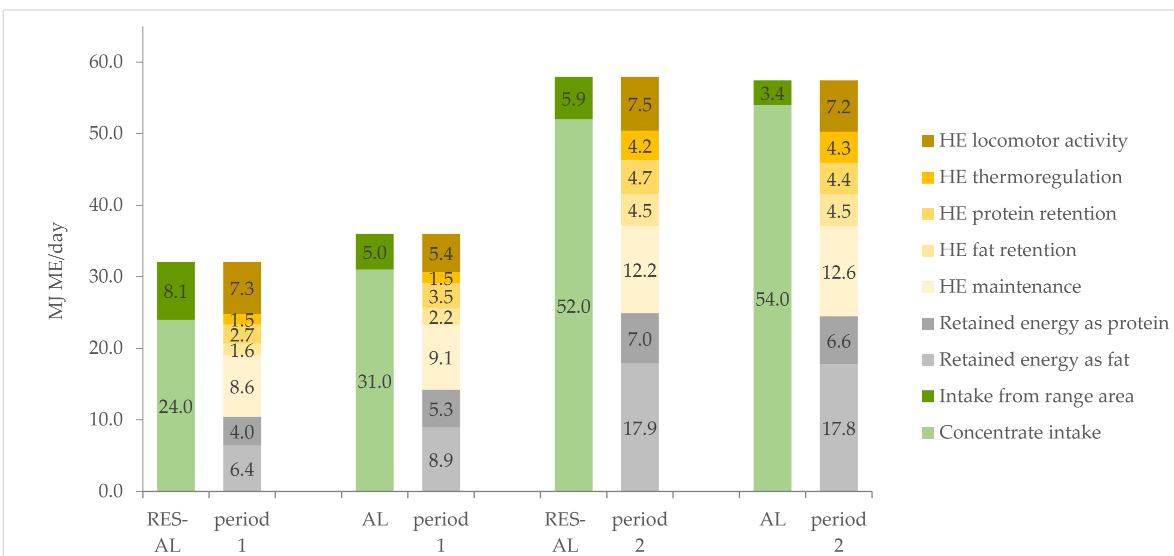

Fig. 3. Daily energy requirements for maintenance, growth as RPE (retained protein energy) and RFE (retained fat energy), thermoregulation and locomotive activity. Total daily energy requirements, intake from concentrate, intake from pasture and share of daily energy requirements covered by foraging. All results are presented in MJ metabolizable energy (ME).

restrictedly fed pigs had only partially compensated growth at time of slaughter.

In the present study, RES-AL pigs increased their ADFI to the level of AL pigs within a few days after transition to ad libitum concentrate supply. The general high ADFI for RES-AL and AL pigs may be associated with various factors such as air temperature, physical activity levels, thermoregulation, genotype, stress level, as well as concentrate supply and composition. Variations in daily concentrate intake seem to be coinciding with allocation of new pasture area, which is known to motivate foraging activity (Wood-Gush et al., 1990; Stern and Andresen, 2003; Rivero et al., 2017). Calculations of concentrate intake are based on paddock level intakes, and can therefore vary among individuals.

In contrast to our expectations, the feeding strategies did not affect FCR significantly in any of the periods. Feed efficiencies of 34.2 and 34.5 MJ ME/kg LW gain were generally high. Previous studies by Kongsted et al. (2013) and Strudsholm and Hermansen (2005) found poorer concentrate efficiencies for free-range ad libitum fed finisher pigs (42.8 MJ ME/kg LW gain and 42.3 MJ ME/kg LW gain). These results are supported by farm data, collected by Rudolph (2015), which confirm markedly lower feed efficiencies in commercial free-range systems across Europe. For comparison, the Danish average FCR of indoor conventional growing-finishing pigs with an ADG of 950 g was 34.2 MJ ME per kg LW gain in 2016 (Helverskov, 2017).

Three important regulators seem to determine the probability of complete compensatory growth, namely degree of restriction, duration of restriction and length of realimentation (Oksbjerg and Therkildsen, 2007). Especially length of restriction may have great influence on the effect of compensatory growth as well as stage of development when restriction is onset. Based on several studies, Skiba et al. (2006) found a more pronounced compensatory growth response when realimentation was initiated at a younger age. They compared introduction of realimentation at 50 kg and 80 kg LW, and concluded that the compensatory growth effect was happening a few weeks after transitioning from restriction to realimentation, mainly because of increased ADFI. Identifying whether this is occurring in the current study would have required more frequent weighing. A shorter duration of restriction, *i.e.* ending on day 42 instead of day 51 for RES-AL pigs, may have had a positive effect on the compensatory growth response. Severity and duration are therefore important parameters that should be further investigated. Especially in pasture based systems where pigs have the opportunity to supplement their daily nutrient intake from various forage crops.

4.2. Carcass quality

Pigs responded similarly to the two feeding strategies with regard to lean meat percentage and back fat thicknesses. Lean meat percentages were within the level of Danish growing-finishing pigs and earlier studies with free-range pigs (Lebret, 2008; Kongsted et al., 2016). Earlier results from restricted feeding of free-range pigs have shown increased lean meat percentage and feed efficiency, but also reduced growth rates, reduced back fat measures and impaired meat quality (Kongsted et al., 2016; Kongsted and Therkildsen, 2014). Interestingly, the Topigs Norsvin TN70 pigs had clearly a greater lean meat percentage than LY pigs.

4.3. Intakes from the range area

Nutritional requirements for maintenance and growth of indoor growing-finishing pigs is generally well known. In contrast, there is limited literature on energy requirements for free-range growing-finishing pigs, and energy requirements were expected to be considerably higher due to thermoregulation and locomotive activity (Edwards, 2003; Eskildsen et al., 2020b).

Estimations of intake from foraging indicate that RES-AL pigs covered a significant part of their daily energy requirement from the range area in period 1 (25%) when the pigs had restricted access to concentrate. Previous studies support this estimate as restricted fed growing-finishing pigs were able to cover up to 26% and even 60% of their energy requirements from foraging grass clover pastures (Kongsted et al., 2015) and root crops (Kongsted et al., 2013), respectively. Despite ad libitum access to concentrate in period 1, AL pigs also covered a considerable part of their daily energy requirements from grazing and rooting (14%) in the current study. Generally, energy intakes from foraging contributed to the high concentrate feed efficiencies observed in the current study as it is not taken into account when evaluating this trait.

Feeding regime had a marked effect on foraging behavior (unpublished data), and RES-AL pigs reduced their share of daily energy requirement covered by intakes from the range area by 60% during realimentation compared to the period with limited access to concentrate. The decline was partly ascribed to the higher concentrate intake and increased age reducing the motivation for foraging behavior and physical activity in general. A similar trend was identified in the behavior of AL pigs, for whom the decline in share of foraging of requirements was 57% from period 1 to period 2. Despite ad libitum access to concentrate in period 2 for all pigs, the share of foraging of daily energy requirements was 40% greater for RES-AL than for AL pigs.

Energy estimations are a simplification and associated with great uncertainty. Especially estimations for energy requirements for thermoregulation and locomotive activity. Indeed, it is not clear whether free-range pigs have an energy need for locomotive activity 2.5 times higher than indoor pigs. Free-range pigs are expected to have an increased locomotive activity level in comparison with indoor pigs, but few estimates have been reported in the literature (Edwards, 2003). Energy requirement for locomotive activity depends on time spend standing, distance walked, level of acceleration, grazing and rooting behavior, and LW of the animal. An energy need for locomotive activity 2.5 times higher than indoor pigs was based on Jakobsen et al. (1994) and behavioral observations showed high activity among pigs, especially rooting behavior when fresh pasture was allocated.

Uncertainties are also considerable when estimating energy for thermoregulation. Any deviation from pigs' thermoneutral zone will increase heat production, either to maintain a constant body temperature at low ambient temperature or increased respiration at high ambient temperature. The lower critical temperature varies greatly and is influenced by numerous conditions such as bedding material, humidity, body condition and wind speed. Consequently, LCT in free-range systems is not well defined, but is proposed to be 21̊C (Quiniou et al., 2001). Close and Poornan (1993) proposed energy requirements for cold thermogenesis to range between 15 and 18 kJ ME/LW ($kg^{0.75}$)/day/̊C below LCT, why the energy requirement for cold thermogenesis was set to 17 kJ ME/LW ($kg^{0.75}$)/day/̊C below LCT. Additionally, the estimation of energy requirements based on average temperatures may be overestimated as the pigs had access to insulated huts with straw, and finally, it is uncertain whether pigs have an energy need for thermoregulation when they ingest 2.4 to 3.7-fold energy more than their energy requirement for maintenance.

Besides energy for locomotive activity and thermoregulation, an increase in ME intake above maintenance increases the heat production (incremental heat) due to retention of fat and protein energy (Theil et al., 2020). Further studies are needed to verify the estimates in the current study.

On average, AL pigs and RES-AL pigs had daily access to 3.6 m^2 and 3.5 m^2 pasture, respectively, throughout the experimental period. In period 1, the daily access was 3.5 m^2 for all pigs, while the daily access in period 2 was 3.7 m^2 for AL pigs and 3.6 m^2 for RES-AL pigs. The average herbage availability was 1148 kg DM per hectare. The estimated average daily availability of herbage was thus 0.40 kg DM/pig in period 1 across treatments and 0.42 kg DM and 0.41 kg DM/pig for AL pigs and RES-AL pigs in period 2. Analysis of grass clover samples showed that the average energy content of herbage was 6.5 MJ ME/kg DM. Assuming that pigs ingested all available forage crop, the daily energy intake corresponded to 2.6 MJ ME/pig in period 1 across treatments and 2.73 MJ ME/pig for AL pigs and 2.77 MJ ME/ pig for RES-AL pigs in period 2. Hence, intakes that are markedly lower than estimated energy intakes from foraging based on growth and requirements for maintenance, thermoregulation and activity. To this should be added that it is unlikely that all available grass clover was ingested, and that the degree of utilization depends on various factors such as nutritive value, including proportion of fibers and digestibility of crude protein, which was not investigated in the present study. This indicates that grass-clover intake was most likely supplemented by consumption of roots, earthworms, or other energy sources below the soil surface. Foraging in the soil may constitute valuable nutritional contributions in pasture-based systems as discussed in Jakobsen et al. (2015) and Studnitz (2019).

5. Conclusions

Results from the present study indicate a great potential for high daily weight gains and feed efficiencies in a mobile pasture system. Compensatory growth response was only partly achieved, and more investigation of an optimal restriction and realimentation period is necessary to obtain full effect of such feeding strategy. Energy requirement calculations based on growth performance and estimates of energy requirements for maintenance, thermoregulation, and locomotive activity, indicate that pigs across treatments covered a considerable share of their daily energy requirements from direct foraging. Overall, the study shows interesting possibilities for rearing free-range pigs in mobile pasture systems. There is a need for further investigation of free-range growing-pigs' energy and nutrient requirements under various outdoor conditions to support development of sustainable feeding strategies and compound feed mixtures.

CRediT authorship contribution statement

L. Juul: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **T. Kristensen:** Methodology, Writing – review & editing, Supervision. **P.K. Theil:** Methodology, Validation, Formal analysis, Writing – review & editing, Supervision. **M. Therkildsen:** Writing – review & editing. **A.G. Kongsted:** Conceptualization, Methodology, Validation, Formal analysis, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare no conflict of interest. The funders had no role in the design of the study, the collection of data, data analyzes or interpretation of data, the writing of the manuscript or to publish the results.

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