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Neutering increases the risk of obesity in male dogs but not in bitches — A cross-sectional study of dog- and owner-related risk factors for obesity in Danish companion dogs

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ABSTRACT

Knowledge of risk factors for canine obesity is an important pre-requisite of effective preventative strategies. This study aimed to investigate risk factors for canine obesity in adult companion dogs across Zealand, Denmark.

Client-owned dogs (> 2 years of age and without chronic illness) were recruited and examined at eight companion animal veterinary practices in areas with varying socio-economic characteristics. The body condition score (BCS) of the dogs was examined by two investigators based on a 9-point scoring scheme. Dog owners answered a questionnaire that had prompts regarding: 1) dog characteristics, including neuter status, 2) owner characteristics, 3) feeding and exercise practices and 4) the owners' attachment to the dog. The effect of these factors on BCS and the risk of being heavy/obese (BCS scores 7–9) were analysed in two separate analyses.

A total of 268 dogs were included in the analysis, of which 20.5% were found to be heavy/obese. The average BCS was 5.46. In terms of dog characteristics, neutering dramatically increased both BCS and the risk of being heavy/obese in male dogs but not in bitches. BCS and the risk of being heavy/obese increased in senior bitches and decreased in senior male dogs. The risk of being heavy/obese was higher in dogs with overweight and obese owners. Regarding feeding and exercise practices, providing only one meal per day increased BCS and risk of being heavy/obese. Treats during relaxation increased the risk of dogs being heavy/obese. It also increased the dogs' BCS, but only if the owners were overweight or obese. An increased duration of daily walking increased the risk of the dog being heavy/obese, but only if the owner was overweight or obese. Allowing the dog to run free in the garden/property decreased the risk of the dog being heavy/obese. The owners' attachment to the dog was not associated with the dogs' BCS or dogs' being heavy/obese.

An important and novel finding was that neutering increased the risk of being overweight or obese for male dogs while bitches were at risk irrespective of neuter status. Furthermore, a complex interaction between owners' weight status, feeding practices and the risk of dogs being overweight or obese was found, which stresses the need to consider companion animal obesity from a One Health perspective in future prospective studies. Finally, this study was unable to confirm that canine obesity is a product of owners being too attached to their dogs.

1. Introduction

Being overweight or obese, is the most frequent form of malnutrition among companion dogs, at least across Western countries, where the proportion of overweight and obese dogs has been reported to range between 19.7–59.3% (Mason, 1970; Edney and Smith, 1986; Robertson, 2003; McGreevy et al., 2005; Colliard et al., 2006; Lund et al., 2006; Courcier et al., 2010a; Corbee, 2013; Mao et al., 2013; Montoya-Alonso

Abbreviations: BCS, body condition score; BMI, body mass index; LAPS, Lexington Attachment to Pets Scale; PCA, principal component analysis; WSAVA, World Small Animal Veterinary Association

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et al., 2017). The prevalence of Danish dogs being overweight or obese has not yet been studied, but it is likely to follow the trend found in other Western countries. Whether human obesity should be categorized as a disease itself is controversial, but there is general agreement that it predisposes individuals to several debilitating diseases (Bray et al., 2017). Similarly, obesity is a major health concern in dogs, increasing the risk of developing diseases such as osteoarthritis and dyslipidemia, and decreasing life expectancy (Kealy et al., 2002; Salt et al., 2019). In both humans and dogs, the recommended treatment involves weight loss plans with significant food restriction, typically in combination with increased physical activity. Unfortunately, the success rate of these programs is often limited, and any weight loss achieved is frequently followed by subsequent weight gain (German et al., 2007, 2012; Flanagan et al., 2017; Greaves et al., 2017). Implementing successful preventive strategies therefore seems to be the key to limiting obesity in our dog population. However, to be able to do this in an evidence-based manner, we need to know more about the risk factors of canine obesity.

Previous studies identified a number of factors that seem to increase the risk of obesity in dogs. These risk factors include characteristics of both the dog and the owner, as well as feed management and exercise. Female dogs have been reported to be more prone to obesity than male dogs (Mason, 1970; McGreevy et al., 2005; Colliard et al., 2006; Lund et al., 2006; Sallander et al., 2010; Mao et al., 2013; Usui et al., 2016; German et al., 2017b), and neutering (Edney and Smith, 1986; Robertson, 2003; McGreevy et al., 2005; Colliard et al., 2006; Lund et al., 2006; Mao et al., 2013; Usui et al., 2016; German et al., 2017b) and increasing age (Robertson, 2003; Colliard et al., 2006; Courcier et al., 2010b; Mao et al., 2013; German et al., 2017b) have often been identified as additional risk factors. Some studies found that middle-aged dogs (6–10 years) were at higher risk compared to dogs older than 10 years of age (Mason, 1970; Kronfeld et al., 1991; McGreevy et al., 2005; Lund et al., 2006; Usui et al., 2016). Owner characteristics that have been found to be risk factors for obesity in dogs include increasing age (Mason, 1970; Courcier et al., 2010b), having a lower income (Kienzle et al., 1998; Courcier et al., 2010b) and being retired (Colliard et al., 2006). Furthermore, some studies have found that obese dogs are more likely to have obese owners (Mason, 1970; Kienzle et al., 1998; Courcier et al., 2011; Montoya-Alonso et al., 2017), although one recent study did not find this association (Munoz-Prieto et al., 2018). Conflicting results have also been found with regard to feeding and exercise regimes. Some studies found that overweight or obese dogs were more frequently offered snacks or treats (Kienzle et al., 1998; Robertson, 2003; Bland et al., 2009; Courcier et al., 2010b; Heuberger and Wakshlag, 2011) and were more likely to be fed homemade food and table scraps as their main diet (Mason, 1970; Lund et al., 2006; Sallander et al., 2010). Other studies have found no difference in the choice of main meal for obese and normal-weight dogs (Edney and Smith, 1986; Kienzle et al., 1998; Gerstner and Liesegang, 2017). Feeding once a day (Robertson, 2003; Colliard et al., 2006; Bland et al., 2009; Munoz-Prieto et al., 2018) or more than three times a day (Bland et al., 2009) have been identified as risk factors for canine obesity, while one study found that feeding once per day decreased the risk of obesity (Mao et al., 2013). A higher level of exercise was linked to a decrease in the risk of obesity in dogs in some studies (Robertson, 2003; Bland et al., 2009; Courcier et al., 2010b; Mao et al., 2013; Raffan et al., 2015; German et al., 2017b; Munoz-Prieto et al., 2018), while other studies were unable to identify an effect of exercise level (Sallander et al., 2010; Gerstner and Liesegang, 2017). A number of studies have investigated the impact of the owner-dog relationship on canine obesity. In one study, the human-animal bond for owners of obese dogs was similar to the bond for owners of normal-weight dogs (Kienzle et al., 1998). However, the authors found that owners of obese dogs had a tendency to anthropomorphize their dogs, as they more often allowed them to sleep in their bed, talked to them and spent more time with the dog while feeding them (Kienzle et al., 1998). This was confirmed in a later study, in which owners of obese dogs were more likely to view their dog like a baby and let it sleep in their bed (German et al., 2017a). Furthermore, a study that used the Lexington Attachment to Pets Scale (LAPS) to investigate the level of attachment between owners and their dogs showed that owners with a high BMI were more attached to their dog (Stephens et al., 2012), pointing to a possible interaction between owner BMI and attachment to the dog as a risk factor for canine obesity.

While most studies have focused on individual risk factors, there may be good reason to direct attention toward the interaction among identified risk factors. For instance, does an obese owner walk the dog as often as a lean owner? Do lean owners feed their dog differently from obese owners? Do lean and obese owners interact differently with their dogs and does that affect the dogs' body condition?

In the current cross-sectional study, we wanted to investigate risk factors for canine obesity in a population of adult dogs and their owners recruited at Danish veterinary practices, and to investigate possible interaction effects of owner weight status and feeding and exercise practices. As different risk factors may apply at different levels of a dog's weight status, we decided to investigate risk factors for the entire weight spectrum of dogs, as well as for the dog being heavy/obese (body condition score (BCS) 7–9/9). The following risk factors were examined: 1) dog characteristics including neuter status, 2) owner characteristics, 3) feeding and exercise practices and 4) the owner's attachment to the dog. Furthermore, we studied 5) whether interactions between owners' weight status and feeding and exercise regimes served to explain the dogs' weight status.

2. Materials and methods

2.1. Participants and recruitment

Participating owners and dogs were recruited at eight companion animal veterinary practices across Zealand, Denmark (the island making up the eastern part of the country including the capital city and just less than half of the country's population). To achieve variation in terms of the socio-economic profile of the dog owners, some of the selected practices were located in the capital region of Copenhagen, while others were in suburban or rural areas. These were selected based on official records of population density and average income to ensure a representative spread of these demographic factors. Four practices were large referral hospitals, including the University Hospital for Companion Animals, University of Copenhagen, while the other three of these were corporate. Two of the referral hospitals were situated in Copenhagen, one was in the suburbs of Copenhagen and one was situated a 1 -h drive south of Copenhagen. Four practices were smaller clinics (one of which was corporate) located between 30 min and 1 h's drive north, west or south of Copenhagen. All practices specialized in companion animals and one referral practice included horses as well. The average yearly income per citizen for the selected areas varied between 301,658 DKK/year and 583,331 DKK/year in 2017 (Statistics Denmark, Sejrøgade 11, 2100 Copenhagen, Denmark).

The study was approved by the local administrative and ethical committee at the University Hospital for Companion Animals, and data collection took place during the period 1st March to 2nd June 2017. The dogs included in the study were a convenience sample of dogs presenting at selected veterinary practices. A power calculation was not performed prior to enrolment due to two reasons; first of all, our main focus was the interaction between risk factors and for these interactions there were no prior studies on which to base a sample size calculation. Secondly the data collection was performed in relation to a master student project and the aim was therefore to enroll as many dogs as possible within the set timeframe. Inclusion criteria were that the dog was adult (> 2 years of age) and that the owner accompanying the dog was a primary caretaker of the dog. Exclusion criteria were: gestation, chronic disease such as inflammatory bowel disease, chronic renal failure, diabetes, hyperadrenocorticism, hypothyroidism, locomotor disease, steroid or phenobarbital treatment and being a professional working dog. Scheduled appointments at the veterinary clinics were screened each morning to plan which of the clients to contact when they presented for their consultation. Owners of eligible dogs were approached in the reception area of the veterinary practices and asked to sign an informed written consent form if they agreed to participate in the study.

2.2. Procedures

Body condition scoring was performed according to the 9-point BCS system validated for dogs (Laflamme, 1997) and adapted to the World Small Animal Veterinary Association´s (WSAVA) toolkit, where a score is given based on palpation and visual inspection of the dog's ribs, waist, bony prominences, tail base and abdominal tug. As this system is subjective and to some degree operator-dependent, it is important to calibrate the scoring procedure across investigators, although a 100% match will seldom be achieved. Prior to recruitment, the two student investigators (SG and SSJ) were therefore trained in body condition scoring by a veterinary nurse and a veterinarian (CRB) both experienced in the procedure. The BCS training was undertaken at the University Hospital for Companion Animals, University of Copenhagen. Following this training, the accuracy of the student investigators' scoring was tested using 21 dogs of different breeds owned by staff or students, as well as patients in the weight loss clinic. Each of the 21 dogs were scored by both of the student investigators, as well as by either the trained veterinary nurse or veterinarian. The minimum and maximum BCS scores of the 21 dogs were 2 and 7 respectively, ensuring that a considerable portion of the expected range was covered in the assessment of the students' scoring performance. To assess inter-rater reliability, we calculated two-way mixed effects intra-class correlation coefficients (ICC), referred to as $ICC_{(A,1)}$ by McGraw and Wong (1996) using the *icc* command in Stata v. 14.2 (StataCorp, Texas, USA). The ICC between the nurse/veterinarian and student 1 was 0.88 (95% CI: 0.73;0.95). ICC between the nurse/veterinarian and student 2 was 0.83 (95% CI: 0.63;0.93). ICC between student 1 and student 2 was 0.80 (95% CI: 0.57;0.91). Depending on the source, these coefficients are considered excellent (Cicchetti, 1994) or good (Koo and Li, 2016). Following the training sessions, a final pilot study of 12 dogs was conducted to check the scoring agreement between the two student investigators as well as the clarity of the questionnaire. The pilot study was also carried out at the University Hospital for Companion Animals, University of Copenhagen, where both student investigators scored the body condition of the dogs, and owners were interviewed about the clarity of the questionnaire. The inter-rater reliability between student 1 and student 2 was excellent (ICC 0.91 (95% CI: 0.72;0.97). A small number of alterations were made to the questionnaire based on the feedback from the owners who answered the pilot questionnaire.

When an owner agreed to participate in the study, an informed consent form was signed and the owner was asked to complete a questionnaire either online, on a tablet, or manually, on paper, depending on his or her preference. The questionnaire was produced in the software program SurveyXact (Rambøll Management Consulting, Copenhagen, Denmark) and if the owner chose to fill it out manually, the answers were transferred to the online questionnaire by one of the two student investigators. The questionnaire (Supplementary material 1) included information relating to dog characteristics (age, sex, neuter status and breed), owner characteristics such as socio-demographic information (for example level of education, gender, current work situation and household income), the owners' height and weight as well as feeding and exercise practice. Finally, the owners' emotional attachment to their dog was evaluated using the Lexington Attachment to Pets Scale (LAPS) (Johnson et al., 1992). Following completion of the questionnaire, the dog was weighed and one or both student investigators (SG/SSJ) gave a BCS based on the 9-point BCS score provided by WSAVA (Members et al., 2011). A picture was taken of the owner and dog together to document the case and enable an approximate visual validation of the weight status of the dog and owner. All pictures were deleted following validation.

Table 1
Frequency table of BCS scoring conducted by student 1 and student 2 from a sample of privately owned dogs recruited at eight veterinary clinics across Zealand, Denmark (N = 268).

	Student 1	Student 2	Student 1 and 2	Total
Practice 1	15	0	0	15
Practice 2	65	0	0	65
Practice 3	27	0	0	20
Practice 4	0	20	0	20
Practice 5	0	20	0	12
Practice 6	0	12	0	30
Practice 7	0	30	0	27
Practice 8	26	43	10	79
Total	133	125	10	268

Student 1 and student 2 conducted BCS scoring and collected questionnaire data separately in seven out of the eight veterinary practices. In one out of the eight practices, both student 1 and student 2 conducted BCS scoring and collected the questionnaire data together. Ten dogs, were BCS scored by both student 1 and student 2 (See Table 1).

2.3. Measures

A complete overview of the measures along with descriptive statistics is provided in Table 2. The measures are described in more detail below.

2.3.1. Outcome variables

Body condition score: the observed BCS (described under procedures) was the first of two outcome variables used in the analysis. The second outcome variable, overweight status, grouped the raw BCS scores into two categories, indicating whether the dog was thin/normal-weight/overweight (BCS = 1–6) or heavy/obese (BCS = 7–9).

2.3.2. Dog characteristics

The dog characteristics that were taken into consideration in the analysis were the sex (male or female), neuter status and age of the dog. Based on a previous study, we categorized the age of the dogs into three groups: young (2–3.9 years), middle-aged (4–8.9 years) and senior (≥9 years) (White et al., 2011).

2.3.3. Owner characteristics

A number of socio-demographic characteristics including the gender, age and educational qualifications of the owners were included in the analysis. Furthermore, information about the type of housing in which the owner/dog lived and family composition (single or multiple adults; presence of children) was included in the analysis. Owner weight status was measured through owner self-reporting of body weight (kilograms) and height (meters). After calculating BMI (BMI = $kg/meter^2$), we categorized the weight status of the owner into slim/normal-weight (BMI < 25), overweight (BMI = 25.01–29.99), obese (BMI > = 30) and not reported. We used the aforementioned LAPS scale (Johnson et al., 1992) to assess owner attachment to the dog. Following the guidelines in Johnson et al. (1992), including reverse coding of two items, all 23 LAPS items were summated to indicate a single measure of attachment. It is possible to divide the attachment scale into three sub-scales that the original scale developers labelled "general attachment", "people substituting", and "animal rights/animal welfare" (Johnson et al., 1992). However, since initial analysis did not

Table 2

Descriptive statistics regarding dog and owner characteristics, feeding practices and dogs' activity levels based on a sample of owners and their dogs recruited at veterinary practices across Zealand, Denmark (N = 250–268)*.

	N	%	Mean (SD)
Dog characteristics			
Sex			
Bitch	145	54.10	
Male	123	45.90	
Neutering status			
Neutered	110	41.04	
Not neutered	158	58.96	
Sex and neutering status			
Intact bitch	82	29.58	
Neutered bitch	63	23.79	
Intact male	76	28.95	
Neutered male	47	17.68	
Age			
Young (2-3 years)	50	18.66	
Middle-aged (4-8 years)	134	50.00	
Senior (≥9 years)	84	31.34	
Breed			
Pure breed	214	79.85	
Cross breed or unknown	54	20.15	
Owner characteristics			
Sex			
Male	81	30.22	
Female	187	68.78	
Age (in years)			49.85 (13.83)
Education			
Compulsory school (9^{th} – 10^{th} grade)	36	13.43	
High school	13	4.85	
Vocational	59	22.01	
Tertiary (2-4 years)	106	39.55	
Higher Tertiary (> 4 years)	54	20.15	
Household income			
0-399,999 Danish Kroner	70	24.76	
400-599,999 Danish Kroner	57	22.83	
600-899,999 Danish Kroner	50	18.01	
≥900,000 Danish Kroner	52	18.33	
Income unknown	39	16.08	
Single or two-adult household			
Single	58	21.64	
Two adults	210	78.36	
Children in household			
No	159	59.33	
Yes	109	40.67	
Housing			
Farm/house in countryside	41	15.30	
House with garden	156	58.21	
Apartment/other	71	26.49	
Owner weight status			
Slim/normal weight	116	49.57	
Overweight	70	29.91	
Obese	27	11.54	
Not reported	21	8.97	
Owner attachment to dog (LAPS)[**] (N = 262)			48.55 (11.90)
Dog's activity level and feeding practices			
Walk (minutes per day) (N = 254)			26.73 (35.50)
Activities (minutes per day)[A] (N = 250)			66.28 (41.78)
Dog can run free			
No	161	60.07	
Yes	107	39.93	
Number of daily meals			
Once per day	52	19.40	
Twice per day	166	61.94	
Three or more times per day	13	4.85	
Ad libitum	37	13.81	
Treats during activities[C]			
Yes	180	67.16	
No	88	32.84	
Treats during relaxation[D]			
Yes	123	54.10	
No	145	45.90	

[*] Sample size is 268 unless otherwise stated.
[**] Lexington Attachment to Pets Scale.

[A] Activities included: hunting, swimming, training, agility and playing (with a ball/stick or rope); [B] Whether the dog can go outside/has access to a garden where it can play, sniff, and exercise; [C] Whether treats are given during hair brushing, hair/nail clipping, exercising, following a command, bathing; [D] Whether treats are given as a snack and/or when the owner(s) eat.

suggest that the sub-scales had any individual effect on predicting BCS or the heavy/obese status (BCS ≥ 7), we opted to use the general attachment scale. All 23 items and their frequencies are reported in Supplementary material 2.

2.3.4. The dog's activity level and feeding practices

Three measures centering on the dog's activity level were used. Walk (minutes per day): the average number of minutes per day the dog is walked according to the owner. Activity (minutes per day): the average number of minutes per day the dog is engaged in activities such as hunting, swimming, training, agility and playing (with a ball/stick or rope) according to the owner. Exercise in garden/ on property: whether the dog was allowed out in the garden/ on the property to sniff, play and exercise.

Three measures of feed management were also used. The first was the number of daily meals. The two other measures focused on treats given to the dog, and were constructed following a principal component analysis (PCA) that aimed to identify underlying patterns of responses to seven situations in which treats are given to dogs. The situations were chosen in response to the question: "in which situations does the dog get treats?". The PCA was based on a tetrachoric correlation matrix of the seven items, and we used the eigenvalue > 1 rule to extract components where the components were allowed to correlate, i.e. oblique rotation (Osborne, 2015). The PCA and the construction of two derived variables are described in the Results section.

2.4. Data analyses

This study focused on variables at the individual (i.e. the dog and owner) level. However, the clustering of data across the eight veterinary practices where dogs and their owners were recruited had to be taken into account in the analysis in order to obtain correct estimates of the standard errors. Therefore, mixed effects analyses were employed in all multivariable analyses, with the veterinary practice used as a random intercept. In the analysis of heavy/obese, we employed mixed effects logit models, and in the analysis of BCS we used linear mixed effects models. We chose a linear mixed effects model in the analysis of BCS instead of an ordinal logit model to simplify the presentation of the results, i.e. as average BCS. This choice was justified by the BCS being approximately normally distributed with minor skewness (0.27) and kurtosis (2.87). This was calculated using Stata's *summarize* command where equations are used so that a perfectly normally distributed variable has a skewness of 0 and kurtosis of 3. Furthermore, an ordinal logit modelling of the BCS retains the same significant main effects and interaction effects as those reported using mixed effects linear modelling (see Supplementary material 3 for the full ordinal logit models).

To examine the different factors that could influence the dog's BCS and risk of being heavy/obese (BCS ≥ 7), three separate models were reported. In the first of these (model 1), we analysed the influence of the dog's characteristics, namely the dog's age, gender and neuter status. The main effects of these three variables were entered (and they were retained as control variables irrespective of their significance levels), after which two-way interactions were inserted one by one. Interactions were included if model fit improved, as assessed by Akaike's Information Criterion (Akaike, 1973). Interaction effects were subsequently subjected to pairwise comparisons (using Stata's *pwcompare(pveffects)* command) to identify the particular factors that resulted in significant differences.

In model 2, we added the main effects of the owner characteristics (socio-demographic variables reported earlier, obesity level and attachment to the dog), while retaining the effects from the final best-fitting model identified in model 1.

In model 3, we added variables relating to the dog's activity level and feeding practices. Since we were particularly interested in understanding whether and how the owner's obesity translated into a higher BCS and risk of being heavy/obese (BCS ≥ 7) for the dog, two-way interactions between owner obesity level and all activity and feeding variables were also inserted one by one. Interactions were included if model fit improved, as assessed by Akaike's Information Criterion (Akaike, 1973). Interaction effects were subsequently subjected to pairwise comparisons (using Stata's *pwcompare(pveffects)* command). The software program Stata v. 14.2 (StataCorp, Texas, USA) was used for the statistical analysis and $p < 0.05$ was considered significant.

In model 2, we only report the effects from the owner's obesity level and dog attachment, and in model 3 we include the effects from activity and feeding variables and possible significant interaction effects with owner BMI. The remaining socio-demographic owner characteristics were treated as control variables.

3. Results

3.1. Recruitment

A total of 657 dog owners were contacted about possible enrolment in the study. Of these, 240 declined, giving an overall acceptance rate of 63%. The majority, 52.5% (126/240), declined due to time constraints, while 14.2% (34/240) declined because they felt that their dog was too nervous for the additional examination, 13.8% (33/240) refused to participate in a research study, 12.9% (31/240) had other specific reasons, and finally 6.7% (16/240) had initially volunteered but left without answering the questionnaire or participating in the examination. As a result, 417 dogs were screened for eligibility, of which 146 dogs were excluded for the following reasons: being under two years old 49% (71/146), being primarily hunting or working dogs 8% (12/146), suffering from a chronic disease or being treated with medication that had been defined under the exclusion criteria 30% (43/146) or the accompanying person not being a primary caretaker 14% (20/146). In total, 278 dogs were included in the sample. When reviewing the final questionnaires, 10 participants were excluded due to incomplete data, resulting in 268 dogs with adequate information for inclusion in the following analysis. While a precise response rate cannot be calculated because we do not have information about the eligibility criteria for the dogs with owners who declined to participate, the final response rate was at least 52% ($268/(657_{\text{total contacted}}\text{-}146_{\text{non-eligible}})$.

3.2. Sample composition

The sample included in the current study is presented in Table 2, and it is worth noting that there is an almost even distribution of male and female dogs. For both sexes, a marginally higher number of dogs were intact compared to neutered. Owners were most often women, with men accounting for only 30% of the respondents. This presumably indicates that more women than men take the family's dog to the veterinarian. There were considerable differences in the education level of the owners and household income levels, suggesting that the sample encompassed a wide socio-economic range. The purebred dogs represented 68 different breeds with most breeds being represented by only 1–4 dogs.

3.3. Body composition distribution

The average BCS in the sample was 5.46 ± 1.24. No dogs were severely underweight (BCS 1–2/9), while 4.1% of the dogs were thin (BCS 3/9). The majority of dogs (75.4%) were in the normal-weight to overweight categories (BCS 4–6/9) and 16.4% were in the heavy category (BCS 7/9), while 2.6% and 1.5% were in the obese or grossly obese categories (BCS 8–9/9). In total, 20.5% of the dogs were heavy/obese (BCS 7–9/9, Table 3).

Table 3
Body Condition Score (BCS, proportions and average) and overweight status in a sample of privately owned dogs recruited at veterinary clinics across Zealand, Denmark (N = 268).

Body Condition Score	n	%
1 - emaciated	0	0
2 - very thin	0	0
3 - thin	11	4.1
4 - underweight/low ideal	50	18.7
5 - ideal	82	30.6
6 - overweight	70	26.1
7 - heavy	44	16.4
8 - obese	7	2.6
9 - grossly obese	4	1.5
Average BCS (standard deviation)	*5.46*	*(1.24)*
Dog's overweight status (dichotomized)	n	%
thin/normal weight/overweight (BCS 3-6)	213	79.5
heavy/obese (BCS 7-9)	55	20.5

3.4. Dog characteristics and the interactions between them

In the analysis of dog characteristics that predict BCS (model 1 in Table 4), two significant two-way interactions were identified – both involving the sex of the dog (i.e. neuter status x sex and age x sex, Fig. 1a). Neutering primarily affected the weight status of male dogs, (Fig. 1a, pairwise comparison$_{\text{(male dogs)}}$: $p < 0.001$). In contrast, there was no statistically significant association between bitches being neutered and BCS in post-estimation tests. The significant interaction effect between age and sex was driven by bitches, as BCS increased steadily from young to senior bitches (Fig. 1a). Such a gradient was not observed in males, where the BCS remained at the same level in young and middle-aged dogs. BCS even seemed to decrease in senior male dogs, although this was not found to be statistically significant in the post-estimation analysis (Fig. 1a).

In terms of heavy/obese dogs (model 1, right-hand side of Table 4), the two-way interactions that were identified as predictors of BCS also significantly predicted heavy/obese dogs (i.e. age x sex and neuter status x sex). Neutered male dogs had a much higher risk of being heavy/obese compared to intact males ($p < 0.05$, Fig. 1b), while there were no significant differences between intact and neutered bitches. When considering the interaction of sex and age, young and middle-aged bitches and males had an approximately similar propensity to be heavy/obese (17–22%). The frequency of being heavy/overweight increased dramatically in senior bitches, while the opposite trend occurred in senior male dogs, where the propensity to be heavy/obese decreased (Fig. 1b). The difference between senior bitches and senior male dogs was statistically significant in the post-estimation analysis ($p < 0.05$).

3.5. Owner characteristics, attachment and feeding and exercise practice

In model 2 (also reported in Table 4), the owner's attachment to the dog did not correlate with the BCS of the dog, while the owner's weight status did. Dogs with obese owners had a higher BCS compared with the reference value of slim/normal-weight owners. In model 2, where heavy/obese (BCS ≥ 7) was the outcome variable, the owner's attachment did not predict the risk of the dog being heavy/obese. However, the owner being overweight or obese increased this risk compared with slim/normal-weight owners (Table 4). The predicted BCS and predicted risk of the dog being heavy/obese is reported for different owner weight statuses in Table 5.

Using a PCA, we examined patterns for owners giving their dogs

Table 4
Results from multivariable analyses of predictors of dogs' body condition score (BCS) and the risk of being heavy/obese (BCS 7-9/9) in a sample of privately owned dogs recruited at veterinary clinics across Zealand, Denmark (N = 234–268).

	BCS[A]									Heavy/obese[B]								
	Model 1 (N = 268)			Model 2 (N = 261)			Model 3 (N = 234)			Model 1 (N = 268)			Model 2 (N = 261)			Model 3 (N = 234)		
	Coef.	Std. Err.	p-value	Coef.	Std. Err.	P-value	Coef.	Std. Err.	P-value	Coef.	Std. Err.	P-value	Coef.	Std. Err.	P-value	Coef.	Std. Err.	P-value
Constant	4.976	0.265	0.000	4.478	0.638	0.000	5.215	0.679	0.000	−1.666	0.603	0.006	−1.645	1.519	0.279	0.445	2.111	0.833
Dog's age (reference: young)																		
Middle-aged	0.498	0.266	0.061	0.496	0.265	0.061	0.480	0.264	0.069	0.111	0.596	0.853	0.114	0.652	0.861	0.741	0.910	0.415
Senior	0.942	0.284	0.001	0.907	0.280	0.001	0.774	0.283	0.006	0.785	0.597	0.189	0.814	0.639	0.203	0.824	0.929	0.375
Neutering status (ref: neutered)																		
Not neutered	0.084	0.200	0.676	0.001	0.203	0.998	0.140	0.212	0.508	0.141	0.415	0.733	−0.206	0.460	0.654	0.339	0.653	0.604
Dog's sex (ref: bitch)																		
Male	0.831	0.403	0.039	0.629	0.402	0.118	0.597	0.399	0.134	1.049	0.880	0.233	0.772	0.985	0.433	1.550	1.348	0.250
Neutering x dog's sex																		
Not neutered. male	−0.834	0.298	0.005	−0.733	0.302	0.015	−0.939	0.308	0.002	−1.472	0.662	0.026	−1.728	0.761	0.023	−3.139	1.121	0.005
Dog's age x dog's sex																		
Middle-aged. male	−0.405	0.396	0.306	−0.189	0.399	0.636	−0.048	0.394	0.903	−0.155	0.887	0.861	0.223	0.984	0.820	0.113	1.298	0.931
Senior. male	−1.173	0.429	0.006	−0.973	0.438	0.026	−0.633	0.453	0.162	−1.675	1.000	0.094	−1.819	1.228	0.139	−1.976	1.651	0.231
Owner weight (ref: slim/normal weight)																		
Overweight (25 ≤ BMI** < 30)				0.157	0.171	0.360	−0.058	0.226	0.798				0.999	0.419	0.017	0.016	0.707	0.982
Obese (BMI ≥ 30)				0.702	0.246	0.004	0.137	0.320	0.669				1.370	0.558	0.014	−0.138	1.121	0.902
Not reported				0.228	0.248	0.358	0.103	0.332	0.757				−0.476	0.715	0.506	−1.298	1.306	0.320
Owner attachment to dog (LAPS*)				0.006	0.007	0.355	0.004	0.007	0.552				0.024	0.016	0.137	0.022	0.022	0.319
Walk (minutes per day)							0.002	0.002	0.393							−0.025	0.016	0.115
Exercise (minutes per day)							0.000	0.002	0.884							−0.001	0.006	0.900
Dog can run free in garden (ref: no)																		
Yes							−0.091	0.168	0.587							−1.531	0.581	0.008
Number of daily meals (ref: one)																		
Two							−0.290	0.204	0.155							−1.474	0.598	0.014
Three or more							−0.051	0.383	0.895							−0.128	1.077	0.906
Ad libitum							−0.564	0.267	0.034							−1.692	0.926	0.068
Treat during Activity							−0.239	0.172	0.164							−0.238	0.503	0.636
Treat during Relaxation							0.266	0.219	0.224							1.383	0.509	0.007
Owner weight x Treat during Relaxation																		
Overweight							0.631	0.358	0.078									
Obese							1.223	0.496	0.014									
Not reported							−0.364	−0.62	0.789									
Owner weight x Walk (minutes per day)																		
Overweight																0.039	0.020	0.050
Obese																0.066	0.035	0.058
Not reported																0.012	0.037	0.745

[A] The analyses of predictors of BCS (models 1, 2, and 3) are from a mixed effects linear regression (with the veterinary clinic inserted as random intercept).
[B] The analyses of predictors of overweight status (models 1, 2, and 3) are from a mixed effects logit regression (with the veterinary clinic inserted as random intercept).
* Lexington Attachment to Pets Scale.
** Body mass index.

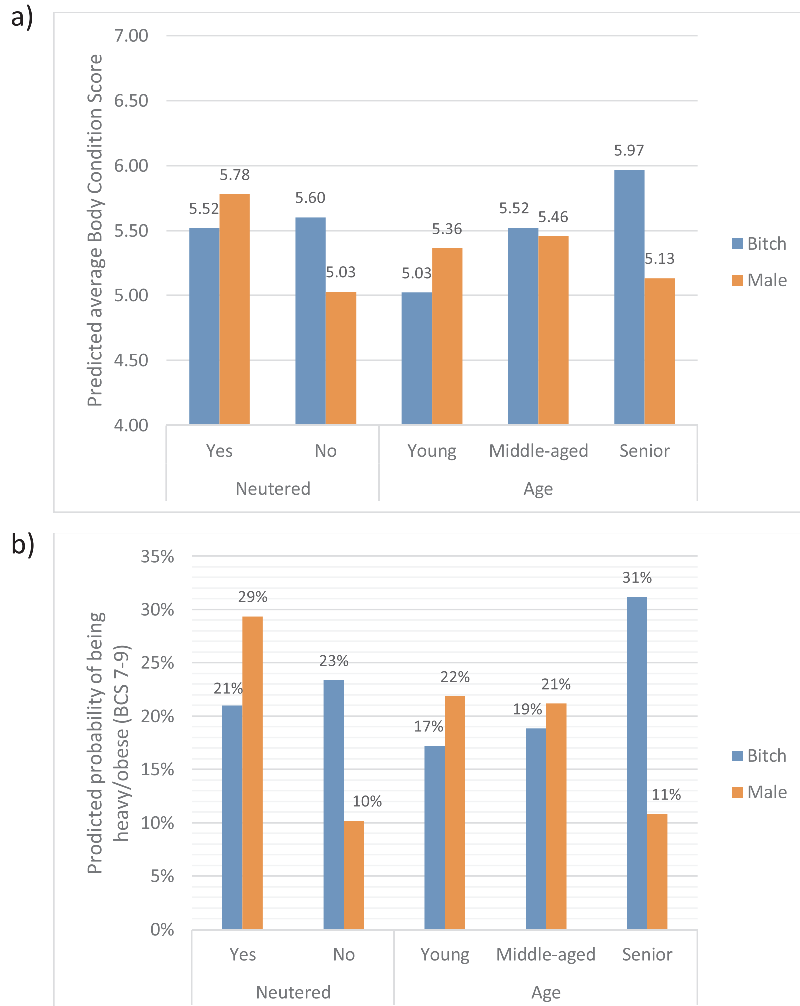

Fig. 1. a) Predicted body condition score (BCS) and b) Predicted probability (reported in %) of a dog being heavy/obese (BCS 7–9/9) based on a mixed effects linear regression (model 1) of different dog characteristics from a sample of privately owned dogs recruited at veterinary clinics across Zealand, Denmark (N = 234).

Table 5
Average body condition score (BCS) and prevalence of heavy/obese (BCS 79/9) dogs stratified by the weight status of their owner in a sample of privately owned dogs recruited at veterinary clinics across Zealand, Denmark (N = 261).

	BCS		Heavy/obese	
	Mean	(95% CI)	Prevalence (%)	(95% CI)
Slim/normal-weight owner	5.29	(5.09;5.50)	14%	(8;21)
Overweight owner	5.45	(5.20;5.71)	28%	(18;38)
Obese owner	5.99	(5.57;6.42)	35%	(18;52)
Unknown owner weight status	5.52	(5.09;5.95)	10%	(0;20)

Predicted average body condition scores (BCS) from a mixed effects linear regression (model 2). Prevalence of heavy/obese dogs are predicted probabilities from the mixed effects logit regression (model 2).

treats (Table 6). Two distinct patterns were identified, namely giving treats during activities (component 1) and treats during relaxation (component 2). On this basis, we constructed two dichotomous variables for use in the subsequent model 3: Treats during Activities (coded 0 = not used; 1 = if owners use one or several of the practices described in component 1 of Table 6) and Treats during Relaxation (coded 0 = not used; 1 = if owners use one or both practices described in component 2).

In model 3, which included the dog's activity level and feeding practices, the dog's BCS was not predicted by the main effects of duration of walking (in minutes), duration of activities the dog was engaged in (in minutes), whether the dog could run free, or whether treats were given during activities. However, providing *ad libitum* feeding had a negative association with BCS ($p < 0.05$). Interestingly, 14% of dogs were fed *ad libitum*. In addition, there was a significant interaction between owner weight status and giving treats during relaxation (Fig. 2). Post-estimation results revealed that the choice of whether or not to give treats during relaxation did not affect the BCS of the dog when the owner was slim/normal-weight. For dogs with overweight owners, the BCS increased when the dog was given treats during relaxation (pairwise comparison$_{(\text{overweight owners})}$ $p < 0.001$). There was an even higher increase among dogs with obese owners (Fig. 2, pairwise comparison$_{(\text{obese owners})}$ $p < 0.001$).

When the dog's activity level and feeding practices were added to the model, the frequency of feeding significantly predicted the risk of the dog being heavy/obese (BCS ≥ 7) (model 3, right hand side of Table 4), as providing two main meals per day resulted in a lower risk compared to only one meal. In addition, if the owners gave their dogs treats during relaxation, this increased the probability of the dog being heavy/obese (BCS ≥ 7) (Table 4). In addition, if the dog was allowed out into the garden or property to sniff, play or exercise, this reduced the risk of the dog being heavy/obese (BCS ≥ 7) (Table 4). Specifically, the predicted proportion of heavy/obese dogs (BCS ≥ 7) was 11.7% among those allowed out into a garden/on a property to sniff, play or exercise and 26.3% among dogs not allowed to do so.

Table 6
Results from the principal component analysis of situations in which treats are given to the dog in a sample of privately owned dogs recruited at veterinary clinics across Zealand, Denmark (N = 268)[*].

	Treats during Activities (component 1 factor loadings)	Treats during Relaxation (component 2 factor loadings)
When hair brushing or hair and nail clipping	0.50	
When going to the veterinarian / groomer	0.47	
When exercising	0.39	
To get the dog to carry out a command	0.40	
When bathing the dog	0.46	
As a snack (e.g. when relaxing with the family)		0.61
When I/we eat		0.68
Eigenvalue	3.1	1.3

* Based on responses to the question "in which situations does the dog get treats?" Factor loadings below 0.30 are not reported in the columns. Tetrachoric coefficients were used as input to the correlation matrix. Reported factor loadings are from an oblimin oblique rotation where components are allowed to correlate with each other (in contrast to an orthogonal rotation where components are not allowed to correlate).

Finally, there was a significant interaction between owner weight status and duration of walking the dog (minutes per day). The pattern of the interaction (depicted in Fig. 3) shows that for dogs with obese owners, as the amount of minutes the dog is walked increased, the probability of the dog being heavy/obese (BCS ≥ 7) also increased (Fig. 3a). A similar pattern could also be seen for dogs with overweight owners, but the increase was not as marked and the slope was less steep (Fig. 3b). In contrast, the risk of dogs with slim/normal-weight owners being heavy/obese decreased, albeit quite modestly, with an increasing time spent on walks (Fig. 3c).

3.6. Model validation

Model validation was carried out on the final model 3, the results of which suggest that the findings were robust. For the linear outcome (BCS), diagnostic tools used to evaluate model assumptions included a visual check of the normality of the standardized residuals (qnorm, pnorm, and histogram), and of constant variance between standardized residuals and fitted values (using a scatter plot). We inspected the graphs visually and detected no problems. In the logit analysis, i.e. the heavy/obese (BCS ≥ 7) outcome, diagnostics used to check model 3 included an inspection of predicted and observed outcomes of the dog being heavy/obese (BCS ≥ 7) when dividing the sample into quantiles and deciles, respectively. There was good agreement between predicted and observed outcomes. The area under the ROC curve (value was 0.8725) also suggested that the model has good predictive ability (Hosmer and Lemeshow, 2000). Furthermore, findings of the linear model were similar to the reported model 3 when deleting three outlier observations on the activities (minutes per day) variable (reduced sample size of linear model = 231). In the logit model, findings were similar when we ran the model after deleting observations with standardized residuals $> +/-2$ as well as the aforementioned three outlier observations (reduced sample size logit model = 221). Finally, we looked for possible non-linear associations between both outcome variables and the three continuous predictor variables (i.e. owner attachment to dog, walk (minutes per day) and activity (minutes per day)), and did not detect any non-linear associations. See Supplementary material 4 for a detailed account of this examination. A complete overview of model 2 and model 3 is appended as Supplementary material 5.

4. Discussion

In this paper, the risk factors for dogs having an elevated BCS or being heavy/obese (BCS ≥ 7) were investigated based on a sample of companion dogs presenting at veterinary practices in Denmark. In light of the existing literature, the discussion will focus on the following risk factors: 1) *Dog characteristics*, with a focus on our findings regarding the effects of neutering, age and sex; 2) *owner characteristics*, with a focus on the effect of the owner's weight status; 3) *owners' attachment* to their dogs; 4) *feeding and exercise practices,* with a focus on the interaction with the owners' weight status. Finally, we will conclude by discussing the strengths and limitations of our study.

Regarding *dog characteristics,* the most important finding of the study concerns the strong effect of neutering on BCS and the risk of becoming heavy/obese (BCS ≥ 7) in male dogs, and the lack of such an effect in bitches. Neutering has long been associated with weight gain and even though a different risk between male and female dogs has previously been identified (Mason, 1970; McGreevy et al., 2005; Colliard et al., 2006; Lund et al., 2006; Sallander et al., 2010; Munoz-

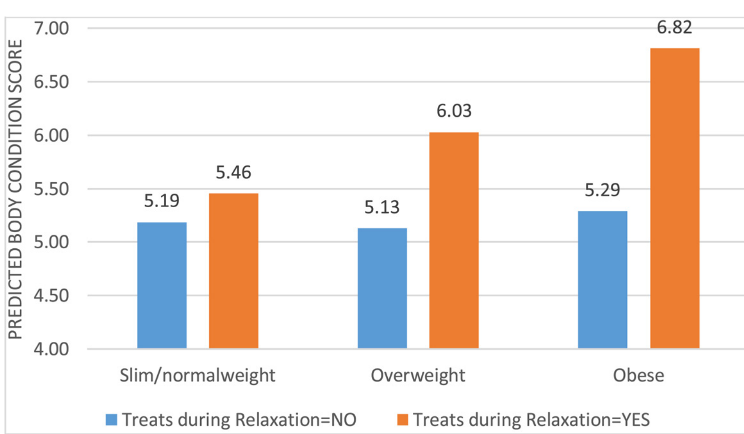

Fig. 2. Predicted body condition score (BCS) of dogs based on a mixed effects linear regression (model 3), stratified by whether treats are given during relaxation and by the owner's weight status from a sample of privately owned dogs recruited at veterinary clinics across Zealand, Denmark (N = 234).

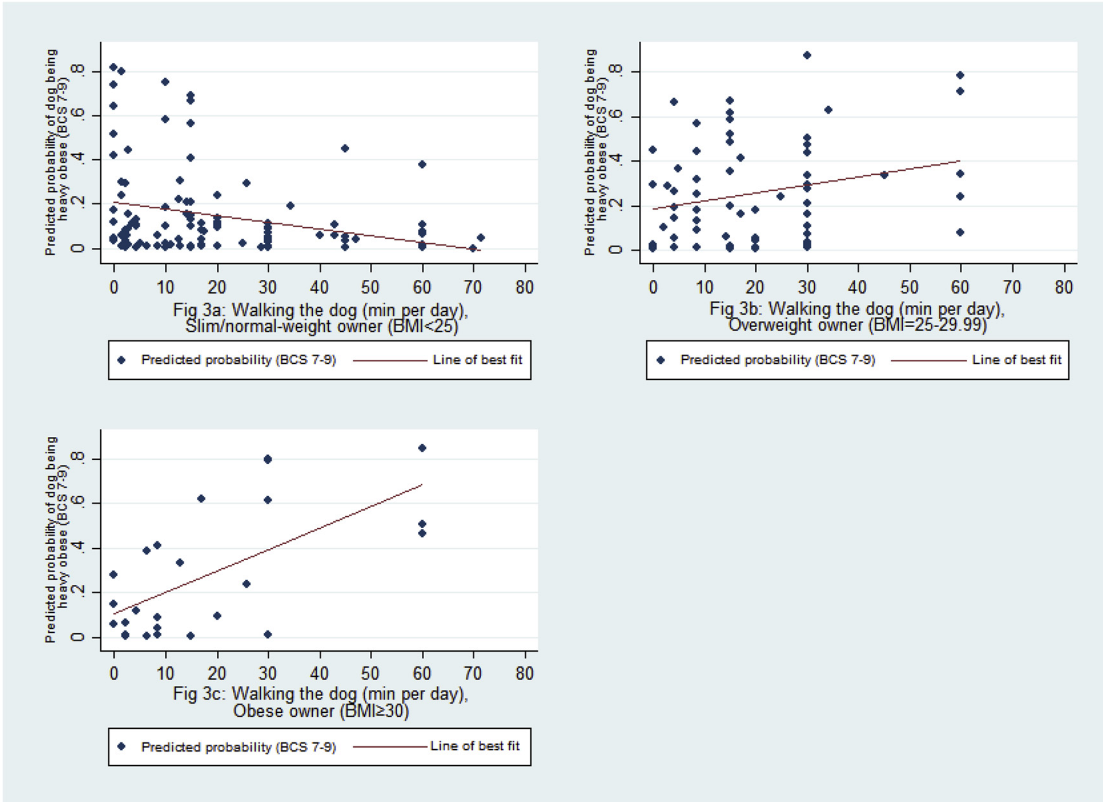

Fig. 3. Scatter plots of predicted probability of a dog being heavy/obese at different levels of walking with the dog (in minutes/day), stratified by the owner's weight status from a sample of privately owned dogs recruited at veterinary clinics across Zealand, Denmark (N = 234) (predicted probability from a mixed effects logit regression; model 3).

Prieto et al., 2018), the interaction between sex and neutering has not been clear. While these results highlight that bitches are at significant risk irrespective of neuter status, and that this increases in their senior years, the risk of developing obesity should perhaps not be deemed a major drawback when considering neutering. On the other hand, our findings confirm that neutering is significantly correlated to BCS increases and to the risk of weight gain and obesity in male dogs. Whether or not to neuter is a decision that should be carefully considered based on many different factors. These include local sociodemographic factors, the risk of overpopulation and transmission of contagious diseases. It is therefore likely that local factors may overshadow the concern for risk of developing obesity in many places. Furthermore, informing owners about this risk could help them to initiate preventive measures such as decreasing the daily ration and increasing exercise to prevent weight gain. However, the results from this study suggest that in countries like Denmark, where there is an efficient legal ban on roaming dogs and the responsibility of dog ownership is regulated by law, the increased risk of obesity in neutered male dogs should be presented to the owner as a possible drawback relating to the decision of neutering. Future studies should address the link between neutering and obesity to corroborate our findings.

The finding that neutering of male dogs correlates with an increase in BCS and the risk of developing obesity could relate to a decrease in circulating levels of testosterone, as it has been shown that a lack of testosterone in humans can lower the metabolic rate and protein metabolism resulting in a lower energy requirement (Mauras et al., 1998). In contrast, no decrease was found in the basic metabolic rate following castration of male cats, instead, the neutering-related increase in body weight was linked to increased food intake (Fettman et al., 1997; Wei et al., 2014). To the authors' knowledge, there are no current studies investigating changes in metabolic rate following the castration of male dogs, though some studies have investigated energy intake following neutering in female beagle dogs (Jeusette et al., 2004, 2006; Schauf et al., 2016). One study of four female beagle dogs indicated a significant reduction in energy requirement 6 months after neutering, but the study did not include a control group of intact bitches, making it difficult to determine whether the reduction was related to neutering or age (Jeusette et al., 2004, 2006). In another study including female beagle dogs, sterilization did not affect voluntary food intake, but significantly decreased the activity level compared with intact control bitches (Schauf et al., 2016). In a recent meta-analysis of energy requirements in dogs, the investigators found a significant decrease in energy requirement of neutered dogs (146.4 ± 21.5 kcal/kg$^{0.75}$) compared with intact dogs (195.7 ± 23.4 kcal/kg$^{0.75}$), while the energy requirement of bitches (163.5 ± 22.6 kcal/kg$^{0.75}$) was similar to male dogs (184.5 ± 22.4 kcal/kg$^{0.75}$) (Bermingham et al., 2014). However, most of the studies included in the meta-analysis did not reveal the distribution of sex in relation to neuter status in the participating dogs, preventing further analyses of energy requirement relating to the interaction of sex and neuter status.

It may be that the differentiated interaction between sex and neutering in dogs has not been described earlier because investigators have not focused on this specific interaction. Furthermore, canine obesity has previously been studied in countries with high (61–87%) (McGreevy et al., 2005; Lund et al., 2006; Laflamme et al., 2008; Heuberger and Wakshlag, 2011; Gerstner and Liesegang, 2017) or very low (1–15%) neutering rates (Sallander et al., 2010; Montoya-Alonso et al., 2017), thus increasing the risk of the previous studies being underpowered compared with the current study, which had a relatively even distribution across genders and neuter status.

We also found that increasing age increased the risk of obesity in female dogs, while it decreased the risk in male dogs. Increasing age has previously been identified as a risk factor (Robertson, 2003; Colliard et al., 2006; Courcier et al., 2010b; Mao et al., 2013; German et al., 2017b), while other studies have identified middle age (6–10 years) as a risk factor compared with being above 10 years of age (Mason, 1970; Kronfeld et al., 1991; McGreevy et al., 2005; Lund et al., 2006; Usui et al., 2016). These reported differences could relate to the sex distribution of dogs in the individual studies, but further studies are required to investigate whether or not a sex-related difference truly exists and, if so, possible explanations for this.

In terms of *owner characteristics*, the study findings of higher BCS scores in dogs with obese owners and a higher risk of dogs with overweight and obese owners also being heavy/obese (BCS ≥ 7) add to the growing awareness of the need to consider companion animal obesity from a One Health perspective (Sandøe et al., 2014). Similar to the current study, other studies have also found that obese dogs are more likely to have obese owners (Mason, 1970; Kienzle et al., 1998; Nijland et al., 2010; Courcier et al., 2011; Montoya-Alonso et al., 2017), while a recent pan-European study did not find this association (Munoz-Prieto et al., 2018). However, the latter study featured an owner estimation of their dog's BCS, which is a potential source of error that may have confounded the results.

A study investigating owner attachment in relation to dog exercise practices found that obese owners were more attached to their dog compared to normal-weight owners (Stephens et al., 2012). Another study that reported a correlation between owner obesity and dog obesity found that despite the measured attachment to the dogs being similar between lean and obese owners, owners of obese dogs more often let their dog sleep in their bed, talked more with the dog and spent more time with the dog while it was eating (Kienzle et al., 1998). This could imply a different relationship to food, feeding or exercise practices in obese owners. However, we did not find higher levels of dog attachment among overweight and obese owners, and dog attachment was not associated with BCS or an elevated risk of the dog being heavy/obese (BCS ≥ 7). We used the LAPS measure in our study to assess owner attachment to their dogs. This measure has been used for several studies since it was first validated (Johnson et al., 1992). It is a score that is based on 23 questions where owners are asked to grade their level of agreement (strongly agree, somewhat agree, somewhat disagree and strongly disagree) in relation to their own perceived attachment to their dog, their dogs' role in people-substitution and the importance of animals rights/animal welfare (Supplemental material, Table S1). It is based on the assumption that the greater the human emotional tie toward a member of another species, the greater the "attachment" is to that member. It has, for instance, been used in a recent Danish study to identify different levels of dog/owner attachment across four dog breeds (Sandøe et al., 2017).

While the degree of attachment was not identified as a risk factor, this study identified significant associations concerning *feeding and exercise practices* that interacted with the owner's weight status. Specifically, we found a positive association between treats given during relaxation and the dogs' BCS among owners that were overweight or obese. In contrast, giving treats during relaxation was a risk factor for dogs being heavy/obese (BCS ≥ 7), irrespective of their owners' weight status. The identified interaction between the owners' weight status and their inclination to give treats during relaxation could indicate that food is used for different purposes depending on the owners' personal weight management.

Further relating to *feeding and exercise practices,* the duration of daily walks with the dog was shown to be an important risk factor in the dog being heavy/obese (BCS ≥ 7), but only among overweight and obese owner groups. Interestingly, there was a positive correlation between the risk of dogs with overweight/obese owners also being heavy/obese (BCS ≥ 7) and the duration of daily walks (while the inverse was true with slim/normal-weight owners). The limited data available makes it difficult to test possible reasons for the rather counter-intuitive finding of a higher risk of dogs being heavy/obese (BCS ≥ 7) with an increased duration of daily walks if owners are overweight/obese. One reason could be that when overweight/obese owners realize that their dog is heavy/obese (BCS ≥ 7), it prompts them to react by increasing the amount of daily walking with the dog (this is probably easier than e.g. altering feeding practices). However, the finding could also be a direct effect of the current study design. Data are based on self-reported activity estimates and it cannot be excluded that overweight/obese owners of heavy/obese dogs overestimate their activity level more than lean owners. Finally, it could relate to the activity intensity – dogs with overweight/obese owners may exercise at a lower intensity compared with lean owners. The speculative reverse-causation hypothesis, as well as the possible confounding effect of self-reported activity levels should be examined using longitudinal data or retrospective interviewing techniques. Furthermore, studies evaluating the intensity of the daily walk and physical activity patterns should be more objectively assessed, for example by applying accelerometers in future controlled prospective studies.

The risk of being heavy/obese (BCS ≥ 7) was considerably lower among dogs that were allowed to run free, for instance in the owner's garden. It was almost exclusively owners who lived in the countryside or had a garden that allowed this (data not shown), while this type of activity obviously had limited applicability to those living in an apartment. Whether being allowed to run free in the garden stimulate an activity level that significantly increase energy expenditure for the individual dog or whether the correlation can be explained by other factors should be further investigated.

The identified difference in the use of snacks during relaxation and activity indicates that feeding and exercise management are likely to differ between slim/normal-weight and overweight and obese owners. Feeding once per day increased the risk of the dog being heavy/obese (BCS ≥ 7) compared with feeding twice per day, which confirms findings from previous studies (Robertson, 2003; Colliard et al., 2006; Bland et al., 2009). It has been speculated that this is related to decreased energy expenditure when the daily ration is digested once a day rather than divided over several meals, but it could also relate to the owners being more likely to feed the dog snacks at other times of the day when only one meal is given. Approximately 14% of the dogs were fed *ad libitum,* and this decreased the average BCS. This could indicate that a minority of dogs are actually able to control their food intake to maintain a normal weight. These findings call for further studies, but may be understood in light of the human studies linking weight control to regular eating patterns and differences in appetite control between individuals.

The current study found no associations with previously identified risk factors relating to owner characteristics including increasing age (Mason, 1970; Courcier et al., 2010b) and being retired (Colliard et al., 2006).

The present study has some *strengths and limitations* that should be considered when evaluating the data. The cross-sectional study design is useful for identifying correlations between different factors and the presence of canine obesity but it does not inform about causality. However, the results may provide a basis for future prospective longitudinal studies. The studies that previously evaluated risk factors for canine obesity were performed in different populations and used different recruitment strategies, as well as inclusion and exclusion criteria. In some studies, BCS was assessed and reported by clinical staff, but not always by the same individuals (Mason, 1970; Edney and Smith, 1986; Kienzle et al., 1998; McGreevy et al., 2005; Colliard et al., 2006; Lund et al., 2006; Courcier et al., 2010b; Mao et al., 2013), while other studies relied on the owners assessing BCS (Robertson, 2003; Bland et al., 2009; Sallander et al., 2010; Munoz-Prieto et al., 2018). Several studies have shown that owners tend to underestimate the BCS if their dog is overweight or obese (Mason, 1970; Colliard et al., 2006; White et al., 2011; Eastland-Jones et al., 2014), even after they have been presented with information and pictures of different BCS scores (Eastland-Jones et al., 2014). In planning the current study, emphasis was put on limiting bias in BCS assessment. The students were trained by skilled personnel and a strong interobserver reliability was established. Furthermore, because the BCS system is poorly validated for use with growing dogs, it was decided that only dogs above 2 years of age would be included. In addition, to avoid including dogs whose body condition was a result of factors other than feed management, dogs diagnosed with chronic disease or given medication that could affect their appetite were also excluded from the analysis. In the analysis, the dogs were divided into two groups based on their BCS: thin/normal weight/overweight (BCS1-6) and heavy/obese (BCS 7–9). It is difficult to define a clear cut-off to describe when a dog has a body fat percentage representing true excess weight based on BCS values. A significant overlap in body fat percentage has been observed in the majority of studies validating the 9-point BCS, especially those including different dog breeds (Laflamme, 1997; Mawby et al., 2004; Jeusette et al., 2010). In the validation study by Laflamme (1997), the body fat percentage of dogs with BCS 5 ranged from 9.6% to 27.5%, while the range for BCS 6 was 14.1–33.3% with a mean for males of 21.7% and 25.7% for females. For BCS 7, the body fat percentage range of 18.5–39.1% still overlapped with BCS 5 and 6, but the means for males (26.2%) and for females (31.4%) were clearly above the 15–20% suggested as a cut-off for normal body fat percentage (Toll et al., 2010). In a later study, Mawby et al. (2004) found the ranges for BCS 6 and BCS 7 to be 14.9–24.4% and 23.1–34.1% respectively, further supporting the notion that in the majority of cases, dogs with a BCS score of 7 have a body fat percentage above normal, while dogs with BCS 6 may more often have a body fat percentage within the normal range.

We had two reasons for setting the threshold for the two categories between BCS 6 and 7. Firstly, there were relatively few dogs with BCS 8 and 9 included in the study data. It was therefore important to increase the number of heavy/obese observations for practical reasons. Secondly, in terms of the potential health effects of excess weight and obesity, we considered it to be safer only to include BCS 7 as heavy/obese.

The body fat percentage at which excess weight becomes a health risk for dogs is currently unknown. Based on a study of lifetime food restriction in Labrador retrievers, the dogs fed *ad libitum* and with a mean lifetime BCS of 6.7 $\pm$ 0.19 and body fat percentage of 29.9% had a shorter lifespan than littermates fed 25% less and with a mean lifetime BCS of 4.6 $\pm$ 0.19 and body fat percentage of 16.8% (Kealy et al., 2002). Though there may be variation among species, the American Council on Exercise (2018) defined the acceptable range of body fat percentage in humans to be 25–31% for women and 18–25% for men. This could indicate that a BCS $\leq$ 6 does not pose a serious health risk. In summary, grouping BCS 7, 8 and 9 resulted in an appropriately sized group of dogs with an unhealthy level of excess weight (by most standards) to serve as a basis for assessing the effects of potential risk factors.

To ensure that our analyses were robust, we decided to include 3 models focussing on specific factors. In the first step, the impact of dog characteristics (model 1) were reported separately as we believe that effects from biological factors should be taken into account before assessing the impact from owner characteristics and feeding/exercise practices. The rationale for model 2 was that we wanted to highlight possible associations among owner characteristics (BMI and attachment to dog) and BCS and the heavy/obese risk (BCS $\geq$ 7) before the feeding/exercise variables were included and studied in interaction with owner obesity level in model 3. Findings were qualitatively similar when including variables in different order (i.e. the main and interaction effects reported in model 3 (Table 4) provided similar results when model 1 and 2 variables were omitted; main effects reported in model 2 in the paper provided similar results when model 1 variables were omitted; model fit improved when model 1 variables (and the identified interactions) were added to model 2 and model 3). We did not include dog breed as a predictor variable, as there was a large variety of purebred dogs and dogs of mixed breed, most of which had quite a low occurrence (as described in Sample Composition in the Results section).

In order to achieve a study population that represented the socio-demographic variation among Danish households, dogs were recruited in veterinary practices across Zealand. Recruiting dogs presenting at veterinary practices may have introduced sample selection bias as owners who do not take their dog to the veterinarian or do so at a slower pace (and hence are less likely to be included in this study than others) may deviate from other owners. Furthermore, the clinics and dogs invited to participate were not chosen at random. As such, the resulting sample is not drawn as a probability sample. In addition, more female than male owners were represented in the survey. This has also been noted in previous studies and could indicate that in families with two genders represented the woman in the household is often the primary caretaker of the pets (Munoz-Prieto et al., 2018).

We chose to study owner-based risk factors at two levels, namely at the high-risk level (i.e. heavy/obese dogs) and at a more general level (i.e. the entire BCS continuum). This resulted in some interesting differences that, when seen in combination, suggest that a sequence of practices co-develop along with an increase in the dog's body weight; in particular among overweight and obese owners. These findings warrant further investigation.

In conclusion, the current study adds to the understanding of risk factors relating to canine obesity. The most important and novel finding is that the effect of neutering on the risk of being overweight or obese depends on the sex of the dog. This finding supports the concerns relating to the negative health effects of neutering male dogs. Furthermore, based on the suggested complex interactions of owner and dog obesity (by which the owner's weight status and feeding practices affect the risk of their dog being overweight or obese), we stress the need to consider companion animal obesity from a One Health perspective. Finally, though demographic differences may exist among studies, this study questions prior assertions that canine obesity is a product of owners being too attached to their dog.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.prevetmed.2019.104730.

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