

1 **Risk factors associated with canine overweightness and obesity in an owner-reported**
2 **survey**

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15 **Abstract:**

16 **Background:** Overweightness and obesity in dogs are associated with negative health
17 outcomes. A better understanding of risk factors associated with canine weight is fundamental
18 to identifying preventative interventions and treatments. In this cross-sectional study, we used a
19 direct to consumer approach to collect body condition scores (BCS), as well as demographic,
20 diet, and lifestyle data on 4,446 dogs. BCS was assessed by owners using a 9-point system and
21 categorized as ideal (BCS 4-5), overweight (BCS 6), and obese (BCS 7+). Following univariate
22 analyses, a stepwise procedure was used to select variables which were included in multivariate
23 logistic regression models. One model was created to compare ideal to all overweight and
24 obese dogs, and another was created to compare ideal to obese dogs only. We then used
25 Elastic Net selection and XGBoost variable importance measures to validate these results.

26 **Results:** Overall, 1,480 (33%) of dogs were reported to be overweight or obese, of which 356

27 (8% total) of dogs were reported to be obese. Seven factors were significantly associated with
28 both overweightness/obesity and obesity alone in all three analyses (stepwise, Elastic Net, and
29 XGBoost): diet composition, probiotic supplementation, treat quantity, exercise, age, food
30 motivation level, and pet appetite. Neutering was also associated with overweightness/obesity in
31 all analyses. **Conclusions:** This study recapitulated established risk factors associated with
32 BCS (age, exercise, neutering). Moreover, we elucidated associations between previously
33 examined risk factors and BCS (diet composition, treat consumption, and temperament) and
34 identified a novel factor (probiotic supplementation). Specifically, relative to dogs on fresh food
35 diets, BCS was higher in dogs eating dry food both alone and in combination with other foods.
36 Furthermore, dogs receiving probiotics, but not other forms of supplementation, were more likely
37 to have an ideal BCS. Future studies should corroborate these findings with experimental
38 manipulations.

39

40 **Keywords:**

41 **Canine, dog, overweight, obesity, diet, dry food, probiotics, treats, fresh food, machine**
42 **learning**

43

44 **Background:**

45 Overweightness and obesity are major health concerns in both humans and companion dogs.
46 Weight issues have been associated with myriad negative health conditions as well as
47 decreased life span (1,2). In the largest study to date, the prevalence of veterinarian-assessed
48 overweightness and obesity of dogs in the United States has been reported to be 34% and 5%
49 respectively (3). Globally, canine overweightness has been determined to range from 6-31% in
50 European countries, 44% in China, 40% in Japan, and 26% in Australia (4–7).

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52 Clinical assessment of overweightness and obesity relies on body condition scores (BCS)
53 based on visual inspection and palpation. A number of studies have identified risk factors
54 associated with increased BCS, including increased age (3-6,8,9), neutering (3,5,6,9,10), and
55 decreased exercise (11,12). Some studies have also identified an effect of different feeding
56 practices. Home-made diets, table foods, semi-moist foods, and canned foods have all been
57 associated with overweightness and obesity (3,12). The consumption of treats and snacks has
58 also been identified as a risk factor (8,10,11). Despite these findings, many of these studies
59 have been limited by comparatively smaller sample sizes (8), or have included only a handful of
60 risk factors (6). Thus, investigating factors associated with canine body weight using a larger
61 cohort and a more comprehensive list of risk factors is warranted.

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63 This study addresses these drawbacks by engaging a direct-to-consumer data collection model
64 wherein a large pool of pet owners distributed widely across the United States completed an
65 extensive online health assessment. The volume of data collected not only allowed us to use
66 standard analytic methods, but also permitted the use of machine learning approaches that do
67 not have the same biases or assumptions of traditional statistical methods. Our results
68 recapitulate findings from previous studies on canine overweightness and obesity, provide
69 additional evidence for factors with conflicting results in the literature, and identify novel factors
70 associated with overweightness and obesity.

71

72 **Results:**

73 Out of a total of 4,446 dogs, 2,967 (67%) were at an ideal weight, defined as an owner-reported
74 body condition score of 4-5 on a previously-validated 9-point system (BCS 4-5; (13)) and 1,480
75 (33%) were overweight or obese (BCS \geq 6). Of these dogs with higher BCS, 1,124 (25% of total)
76 were overweight (BCS 6) and 356 (8% of total) were obese (BCS \geq 7).

77

78 **Identification of Risk Factors Associated with Overweightness and Obesity**

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80 **Significant Risk Factors Identified via Univariate Analysis:**

81 To identify factors associated with increased BCS, we performed two univariate analyses
82 comparing ideal weight dogs (N=2,966) to overweight/obese dogs (N=1,480) as well as to
83 obese dogs only (N=356). Of the 45 variables selected as outlined in Methods, 22 (49%) were
84 significantly associated with overweightness/obesity in a univariate analysis ($p < 0.05$, N=4,446)
85 and 18 (40%) were significantly associated with obesity ($p < 0.05$, N=3,322). The relationships
86 between these variables and BCS are summarized in Table 1. The 18 variables positively
87 associated with both overweightness/obesity and obesity were diet combinations containing dry
88 food, increased treat quantity, lack of probiotic consumption, increased age, decreased exercise
89 per week, neutering, increased pet appetite, increased food motivation, lower overall mood,
90 decreased conspecific interaction, increased tail chasing, decreased prey drive, presence of
91 other dogs in the household, rural home environment, conventional-only medicine type,
92 household tobacco use, food intolerances, and rescue or other acquisition method. Four
93 additional variables positively associated with BCS in the overweightness/obesity analysis were
94 the use of dental chews, sharing or cooking food, increased overall nervousness, and
95 decreased dental visit frequency.

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Table 1: Results of Univariate Analyses							
		Overweight and Obese (N=1480) vs Ideal (N=2966)			Obese (N=356) vs Ideal (N=2966)		
		N (% of 4,446) or mean (SD)	OR [95% CI]	p	N (% of 3,322) or mean (SD)	OR [95% CI]	p
Diet	Fresh Only	1,001 (22%)	Reference		761 (23%)	Reference	
	Kibble Only	938 (21%)	1.45 [1.21-1.76]	<0.0001***	684 (21%)	2.11 [1.52-2.96]	<0.0001***
	Kibble & Fresh	376 (8.5%)	1.31 [1.02-1.68]	0.03*	263 (7.9%)	1.08 [0.64-1.76]	>0.05
	Kibble & Canned	349 (7.9%)	1.85 [1.44-2.38]	<0.0001***	238 (7.2%)	2.56 [1.68-3.87]	<0.0001***
	Canned Only	182 (4.1%)	1.31 [0.94-1.83]	>0.05	134 (4.0%)	1.75 [0.97-3.01]	>0.05
	Raw Only	136 (3.1%)	0.52 [0.32-0.81]	0.005**	116 (3.5%)	0.51 [0.17-1.17]	>0.05
	Dried Only	109 (2.5%)	0.84 [0.53-1.30]	>0.05	86 (2.6%)	0.85 [0.32-1.87]	>0.05
	Other/Unknown	1,355 (30%)	0.98 [0.82-1.18]	>0.05	1,040 (31%)	1.06 [0.75-1.49]	>0.05
Treats	None	325 (7.3%)	Reference		262 (7.9%)	Reference	
	<10 percent	3,535 (80%)	1.13 [0.88-1.46]	>0.05	2,655 (80%)	0.72 [0.49-1.09]	>0.05
	>10 percent	581 (13%)	2.12 [1.59-2.84]	<0.0001***	402 (12%)	2.15 [1.40-3.39]	0.0007***
Probiotics	No	3,602 (81%)	Reference		2,658 (80%)	Reference	
	Yes	844 (19%)	0.65 [0.55-0.77]	<0.0001***	664 (20%)	0.46 [0.32-0.64]	<0.0001***
Age	Years	6.73 (4.09)	1.09 [1.07-1.11]	<0.0001***	6.44 (4.16)	1.10 [1.07-1.13]	<0.0001***
Exercise per week	0-4 hours	1,827 (41%)	Reference		1,296 (39%)	Reference	
	4-7 hours	1,549 (35%)	0.57 [0.50-0.66]	<0.0001***	1,160 (35%)	0.28 [0.21-0.37]	<0.0001***

	7-14 hours	804 (18%)	0.45 [0.37-0.54]	<0.0001***	639 (19%)	0.25 [0.17-0.35]	<0.0001***
	14+ hours	257 (5.8%)	0.29 [0.20-0.40]	<0.0001***	221 (6.7%)	0.19 [0.09-0.35]	<0.0001***
Neutered	No	524 (12%)	<i>Reference</i>		449 (14%)	<i>Reference</i>	
	Yes	3,904 (88%)	2.39 [1.90-3.02]	<0.0001***	2,864 (86%)	2.54 [1.67-4.08]	<0.0001***
Pet Appetite	1-5 scale	1.90 (0.46)	2.16 [1.86-2.51]	<0.0001***	1.88 (0.46)	4.30 [3.28-5.67]	<0.0001***
Food Motivation	1-5 scale	4.00 (1.26)	1.23 [1.16-1.30]	<0.0001***	3.95 (1.28)	1.40 [1.26-1.56]	<0.0001***
Mood	1-5 scale	1.91 (0.93)	1.30 [1.21-1.38]	<0.0001***	1.88 (0.93)	1.50 [1.34-1.67]	<0.0001***
Conspecific Interaction	1-4 scale	2.67 (0.94)	0.81 [0.75-0.86]	<0.0001***	2.70 (0.94)	0.71 [0.63-0.81]	<0.0001***
Tail Chasing	1-5 scale	4.74 (0.74)	1.24 [1.13-1.36]	<0.0001***	4.73 (0.76)	1.54 [1.25-1.97]	0.0001***
Prey Drive	1-5 scale	2.67 (1.29)	0.91 [0.87-0.96]	0.0003***	2.69 (1.30)	0.83 [0.76-0.91]	<0.0001***
Other Dogs	No	2,361 (53%)	<i>Reference</i>		1,775 (53%)	<i>Reference</i>	
	Yes	2,085 (47%)	1.26 [1.11-1.43]	0.0003***	1,547 (47%)	1.81 [1.45-2.27]	<0.0001***
Dental Chews	No	2,786 (63%)	<i>Reference</i>		2,120 (64%)	<i>Reference</i>	
	Yes	1,660 (37%)	1.24 [1.09-1.41]	0.001**	1,202 (36%)	1.23 [0.98-1.54]	>0.05
Share Food/Cook	No	1,768 (40%)	<i>Reference</i>		1,362 (41%)	<i>Reference</i>	
	Yes	2,668 (60%)	1.24 [1.09-1.41]	0.001**	1,953 (59%)	1.19 [0.95-1.50]	>0.05
Home Environment	Urban	1,048 (24%)	<i>Reference</i>		813 (24%)	<i>Reference</i>	
	Suburban	2,736 (62%)	1.22 [1.05-1.43]	0.009**	2,017 (61%)	1.16 [0.88-1.53]	>0.05
	Rural	648 (15%)	1.36 [1.11-1.68]	0.003**	480 (14%)	1.62 [1.14-2.30]	0.007**
Medicine Type	Conventional Only	1,621 (36%)	<i>Reference</i>		1,202 (36%)	<i>Reference</i>	
	Mixed	2,602 (59%)	0.84 [0.74-0.96]	0.01*	1,949 (59%)	0.65 [0.52-0.82]	0.0002***
	Holistic Only	176 (4.0%)	0.67 [0.47-0.95]	0.03*	138 (4.2%)	0.51 [0.25-0.94]	0.04*

Nervousness	1-5 scale	2.36 (1.21)	1.06 [1.01-1.12]	0.02*	2.34 (1.20)	1.09 [0.99-1.19]	>0.05
Household Tobacco	No	4,098 (92%)	<i>Reference</i>		3,070 (92%)	<i>Reference</i>	
	Yes	327 (7%)	1.34 [1.06-1.69]	0.01*	236 (7%)	1.69 [1.16-2.41]	0.005**
Dentist Frequency	1-3 scale	1.56 (0.73)	1.11 [1.02-1.21]	0.02*	1.55 (0.73)	1.12 [0.97-1.30]	>0.05
Food Intolerances	No	3,646 (82%)	<i>Reference</i>		2,714 (82%)	<i>Reference</i>	
	Yes	774 (18%)	0.83 [0.70-0.98]	0.03*	591 (18%)	0.70 [0.51-0.96]	0.03*
Acquisition Method	Breeder	1,930 (43%)	<i>Reference</i>		1,470 (44%)	<i>Reference</i>	
	Rescue	1,657 (37%)	1.25 [1.09-1.44]	0.002**	1,212 (36%)	1.38 [1.07-1.78]	0.0002***
	Other	859 (19%)	1.29 [1.09-1.53]	0.003**	640 (19%)	1.75 [1.31-2.33]	0.01*

OR: Odds Ratio; 95% CI: 95% Confidence Interval; Pet Appetite: 1-Poor, 5-Excellent; Food Motivation Level: 1-Not at all, 5-Very; Mood: 1-Excellent, 5-Depressed; Conspecific Interaction: 1-Never, 4-Often; Tail Chasing Frequency: 1-Never, 5-Multiple times per day; Prey Drive: 1-Never, 5-Very Often; Nervousness: 1-Not at all, 5-Very; Dentist Frequency: 1-Never, 3-Three or more times

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103 *Significant Risk Factors Identified via Stepwise Multivariable Analysis:*

104 Since body weight is a complex trait that can be influenced by multiple variables, we performed
105 multivariate analysis to understand how different variables are associated with BCS when they
106 are taken together. We performed these analyses in the overweight/obese and obese groups
107 separately. The results from the two stepwise logistic regression models comparing ideal weight
108 dogs (N=2,725) to overweight/obese dogs (N=1,384) as well as obese dogs (N=327) are
109 presented in Table 2. Due to missing data in the selected variables, 337 dogs from the total
110 dataset were dropped from this logistic regression. Log odds for significant variables are
111 presented in Figure 1. The variables significantly associated with overweightness/obesity were
112 age, exercise per week, food motivation level, overall mood, pet appetite, sharing food,
113 neutering, treat quantity, probiotic supplements, home environment, diet, and dental treatment
114 frequency ($p < 0.05$, stepwise logistic regression, N=4,109). The variables significantly
115 associated with obesity alone were age, exercise per week, food motivation level, other dogs in
116 the household, overall mood, pet appetite, neutering, tail chasing frequency, treat quantity,
117 probiotic supplements, medicine type, diet, and dental treatment frequency ($p < 0.05$, stepwise
118 logistic regression, N=3,052). The intersection of variables in the two models were age, exercise
119 per week, food motivation level, overall mood, pet appetite, neutering, treat quantity, probiotic
120 supplements, diet, and dental treatment frequency.

121

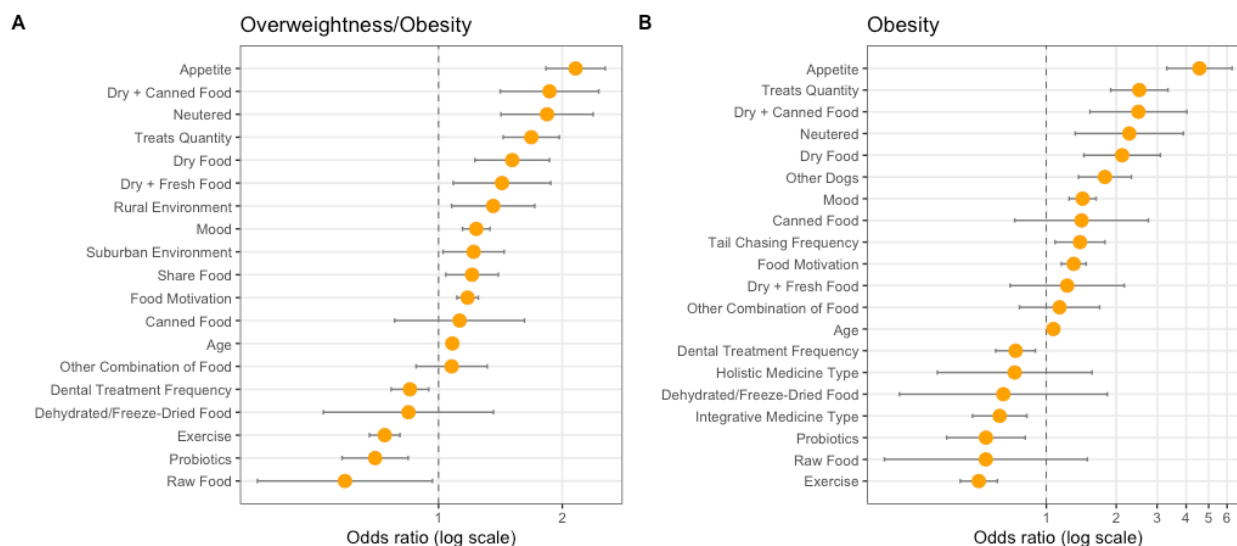
122 Given the nonlinear relationship between age and body condition reported by others (3,5,6,9),
123 age was entered as both a linear and quadratic term in the logistic regression model. In the
124 context of the model, both the linear and quadratic terms had odds ratios that were statistically
125 significant ($p < 0.0001$). The inclusion of the quadratic term significantly improved both the
126 overweight/obese and obese only logistic regression models, as determined by nested model
127 ANOVA ($p < 0.0001$, likelihood ratio test).

Table 2: Final Multivariable Logistic Regression Models					
		Overweight and Obese (N=1384) vs Ideal (N=2725)		Obese (N=327) vs Ideal (N=2725)	
Feature		OR [95% CI]	p-value	OR [95% CI]	p-value
Age	Years	1.58 [1.47-1.70] [B]	<0.0001***	1.82 [1.56-2.14]	<0.0001***
	Years ² [A]	0.98 [0.97-0.98]	<0.0001***	0.97 [0.96-0.98]	<0.0001***
Exercise per week	<4 hours	<i>Reference</i>		<i>Reference</i>	
	4-7 hours	0.67 [0.57-0.79]	<0.0001***	0.32 [0.23-0.44]	<0.0001***
	7-14 hours	0.58 [0.47-0.71]	<0.0001***	0.33 [0.21-0.50]	<0.0001***
	>14 hours	0.45 [0.31-0.65]	<0.0001***	0.25 [0.11-0.57]	0.001***
Diet Composition	Fresh	<i>Reference</i>		<i>Reference</i>	
	Dry	1.47 [1.19-1.82]	0.0003***	2.17 [1.47-3.20]	0.0001***
	Canned	1.11 [0.77-1.61]	>0.05	1.46 [0.74-2.89]	>0.05
	Dehydrated/ Freeze-Dried	0.88 [0.54-1.43]	>0.05	0.65 [0.22-1.87]	>0.05
	Raw	0.57 [0.35-0.93]	0.02*	0.52 [0.19-1.44]	>0.05
	Kibble and Canned	1.93 [1.46-2.56]	<0.0001***	2.64 [1.60-4.34]	0.0001***
	Kibble and Fresh	1.47 [1.11-1.95]	0.007**	1.38 [0.77-2.47]	>0.05

	Other Combination	1.06 [0.87-1.30]	>0.05	1.17 [0.78-1.75]	>0.05
Food Motivation Level	1-5 scale	1.18 [1.11-1.26]	<0.0001***	1.33 [1.17-1.50]	<0.0001***
Other Dogs		ns	ns	1.78 [1.36-2.34]	<0.0001***
Overall Mood	1-5 scale	1.23 [1.14-1.33]	<0.0001***	1.42 [1.23-1.63]	<0.0001***
Pet Appetite	1-5 scale	2.07 [1.75-2.45]	<0.0001***	4.36 [3.13-6.08]	<0.0001***
Share Food or Cook		1.19 [1.02-1.38]	0.03*	ns	ns
Neutered		1.66 [1.28-2.17]	0.0002***	2.15 [1.23-3.76]	0.007**
Dental Treatment Frequency	1-3 scale	0.82 [0.73-0.91]	0.0002***	0.72 [0.59-0.88]	0.001**
Tail Chasing Frequency	1-5 scale	ns	ns	1.30 [1.01-1.69]	0.04*
Treats Quantity	None	<i>Reference</i>		<i>Reference</i>	
	Less than 10%	1.25 [0.95-1.66]	>0.05	1.03 [0.63-1.69]	>0.05
	More than 10%	2.50 [1.80-3.48]	<0.0001***	3.97 [2.27-6.95]	<0.0001***
Supplements Probiotic		0.72 [0.60-0.87]	<0.0001***	0.57 [0.38-0.85]	0.006**
Medicine Type	Conventional	<i>Reference</i>		<i>Reference</i>	
	Integrative	ns	ns	0.67 [0.51-0.88]	0.004**
	Holistic	ns	ns	0.73 [0.33-1.59]	>0.05
Home Environment	Urban	<i>Reference</i>		<i>Reference</i>	
	Suburban	1.21 [1.02-1.44]	0.03*	ns	ns

	Rural	1.35 [1.07-1.72]	0.01*	ns	ns
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128 OR: Odds Ratio; 95% CI: 95% Confidence Interval; Food Motivation Level: 1-Not at all, 5-Very; Mood: 1-Excellent, 5-Depressed; Pet Appetite: 1-Poor, 5-Excellent; Dental Frequency:
 129 1-Never, 3-Three or more times; Tail Chasing Frequency: 1-Never, 5-Multiple times per day
 130 [A] Age as a quadratic term was eliminated from the confirmatory variable selection procedures to maximize interpretability. Note also that XGBoost already handles nonlinearities in
 131 the input features through the potential selection of multiple decision points per variable.
 132 [B] The coefficient of quadratic terms denotes the curvature. In this case the negative coefficient indicates that the curve is concave, with dogs in the middle of the age range at highest
 133 risk.
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135
 136 **Figure 1**
 137 **Title: Variable Log Odds in Final Stepwise Models**
 138 **Legend: Odds ratios for each significant variable in the final model for (A) overweightness and obesity and (B) obesity alone shown.**
 139 **Error bars show the 95% confidence interval for each risk factor. Diet risk factors are shown relative to a fresh diet, home**

140 environment risk factors are shown relative to an urban environment, and medicine type risk factors are shown relative to
141 conventional medicine only.

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143 *Significant Risk Factors Selected via Elastic Net Analysis:*

144 Collinearity poses a major issue for stepwise models, since only a subset of a group of collinear
145 variables may be selected, such that the final ensemble of variables may be influenced by
146 noise. Elastic Net is a method that combines the L_1 and L_2 penalties used in the Lasso and ridge
147 methods, respectively. It addresses the collinearity issue, as it exhibits a grouping effect (14)
148 wherein coefficients of correlated variables tend to be similar. Thus, through the Elastic Net
149 algorithm we may see if any important variables are being masked by their correlations with
150 others.

151

152 For both the overweight/obese and obese only models, the most significant ensemble of risk
153 factors was selected as detailed in Methods. Factors that appeared in both the optimal model
154 for overweightness/obesity and the optimal model for obesity alone were: pet appetite, treat
155 quantity, exercise, probiotic supplementation, diet, mood, food motivation level, and age. The
156 overweightness/obesity model also included neutering, home environment, and sharing food,
157 while the obesity model also included medicine type. With the exception of medicine type, all of
158 these variables are within the subset of those selected by stepwise logistic regression. Variables
159 selected by the Elastic Net are presented in [Supplementary File 1] and [Supplementary File 2].
160 Comparisons between variables selected by Elastic Net and other methods are presented in
161 Table 3.

162

163 *Significant Risk Factors Selected via XGBoost Analysis:*

164 Another issue with the stepwise model is that non-linear effects are not accounted for. We
165 addressed this by using XGBoost, a tree-based machine learning algorithm (15). A tree-based
166 model can establish decision points at multiple different values, and thus the final variable
167 importance in the model encompasses non-linear relationships including interactions between

168 variables. Through XGBoost we may identify which variables, if any, we should examine in
169 terms of higher-order interactions or polynomial models. Factors that appeared in both the
170 optimal model for overweightness/obesity and the optimal model for obesity were: age, pet
171 appetite, exercise, treat quantity, food motivation level, diet, and probiotic consumption. The
172 overweightness/obesity model also included neutering. Each one of these variables was also
173 selected by stepwise logistic regression and Elastic Net. The variable importance plots from the
174 XGBoost models are presented in [Supplementary File 3] and [Supplementary File 4].
175 Comparisons between variables selected by XGBoost and other methods are presented in
176 Table 3.

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178 Healthy Subgroup:

179 We repeated the multivariate logistic regression analysis with only the subgroup of dogs that
180 were reported to have no major health conditions, in order to remove the possibly confounding
181 effects of disease and treatment variables. This subset consisted of dogs that did not have
182 pancreatitis, diabetes, kidney issues, liver disease, heart issues, cancer, or gastrointestinal
183 conditions (N=3,173, 71% of total dataset). Of these dogs, 2,118 (67%) were at an ideal weight
184 (BCS 4-5) and 1,055 (33%) were either overweight/obese (BCS \geq 6) or obese (BCS \geq 7); these
185 were further categorized into 792 (25% of total) that were overweight and 263 (8% of total) that
186 were obese. These proportions were not statistically significantly different from the proportions
187 in the overall sample ($p < 0.05$, χ^2 test). Thirteen of the 15 variables selected from the total
188 dataset remained significant despite decreased power to detect significant effects. These
189 findings are available in [Supplementary File 5]. Due to missingness in the selected variables,
190 192 dogs were dropped from the healthy subgroup logistic regression.

191

192 Individual Contributions of Selected Risk Factors

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194 Among the 7 risk factors identified by all of the eight selection methods (univariate, stepwise,

195 Elastic Net, and XGBoost each undertaken for both overweightness/obesity and obesity alone)

196 [Table 3] were diet, age, exercise, probiotic supplementation, and treat quantity. We further

197 examined the individual contributions of these five risk factors to BCS.

198 **Table 3: Significant variables selected by each protocol**

	Overweightness/Obesity				Obesity			
	Univariate	Stepwise	Elastic Net	XGBoost	Univariate	Stepwise	Elastic Net	XGBoost
Diet	●	●	●	●	●	●	●	●
Probiotic Supplements	●	●	●	●	●	●	●	●
Treat Quantity	●	●	●	●	●	●	●	●
Age	●	●	●	●	●	●	●	●
Exercise	●	●	●	●	●	●	●	●
Food Motivation Level	●	●	●	●	●	●	●	●
Pet Appetite	●	●	●	●	●	●	●	●

Overall Mood	●	●	●	○	●	●	●	○
Other Dogs in Household	●	●	○	○	●	●	○	○
Sharing Food	●	●	●	○	○	○	○	○
Neutered	●	●	●	●	●	●	○	○
Home Environment	●	●	●	○	●	○	○	○
Dentist Frequency	●	●	○	○	○	●	○	○
Tail Chasing Frequency	●	○	○	○	●	●	○	○
Medicine Type	●	○	○	○	●	○	●	○

199 ● $p < 0.05$, ○ $p > 0.05$, Variables were included if they were significant in at least two different models.
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202 Diet:

203 We examined the relationship between the most common diet types and both

204 overweightness/obesity (Figure 2) and obesity alone (Figure 3). Since a fresh food only diet was

205 the largest category (besides “Other”, see Methods) we used this as our reference level in the

206 logistic regression.

207

208 Relative to dogs on a fresh food only diet, dogs fed dry plus canned food (OR=1.85, $p<0.0001$),

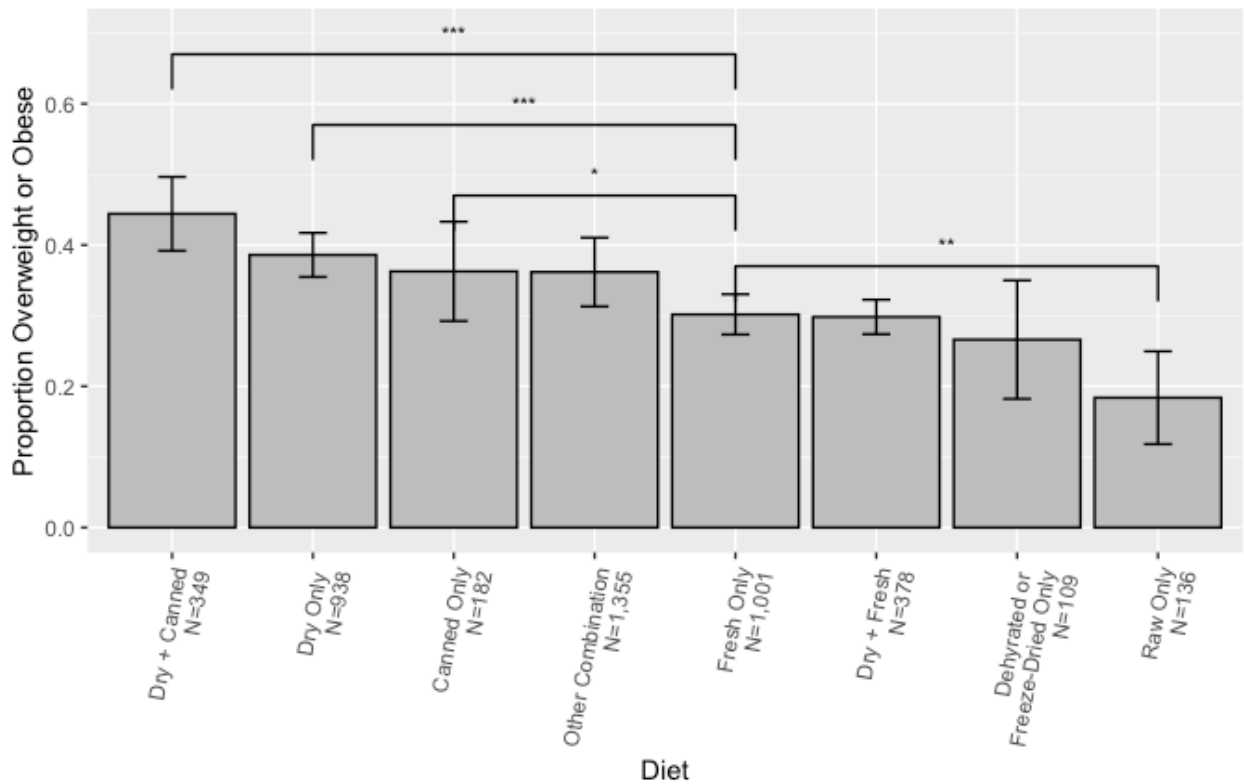
209 dry food only (OR=1.45, $p<0.0001$), and dry plus fresh food (OR=1.3, $p=0.03$) were more likely

210 to be overweight/obese. Dry plus canned food (OR=2.6, $p<0.0001$) and dry food only (OR=2.1,

211 $p<0.0001$) were also risk factors for being obese, but not dry plus fresh food ($p>0.05$). Dogs fed

212 raw food only were less likely to be overweight/obese (OR=0.5, $p=0.005$), but there was no

213 effect on obesity alone ($p>0.05$).



214

215 Figure 2:

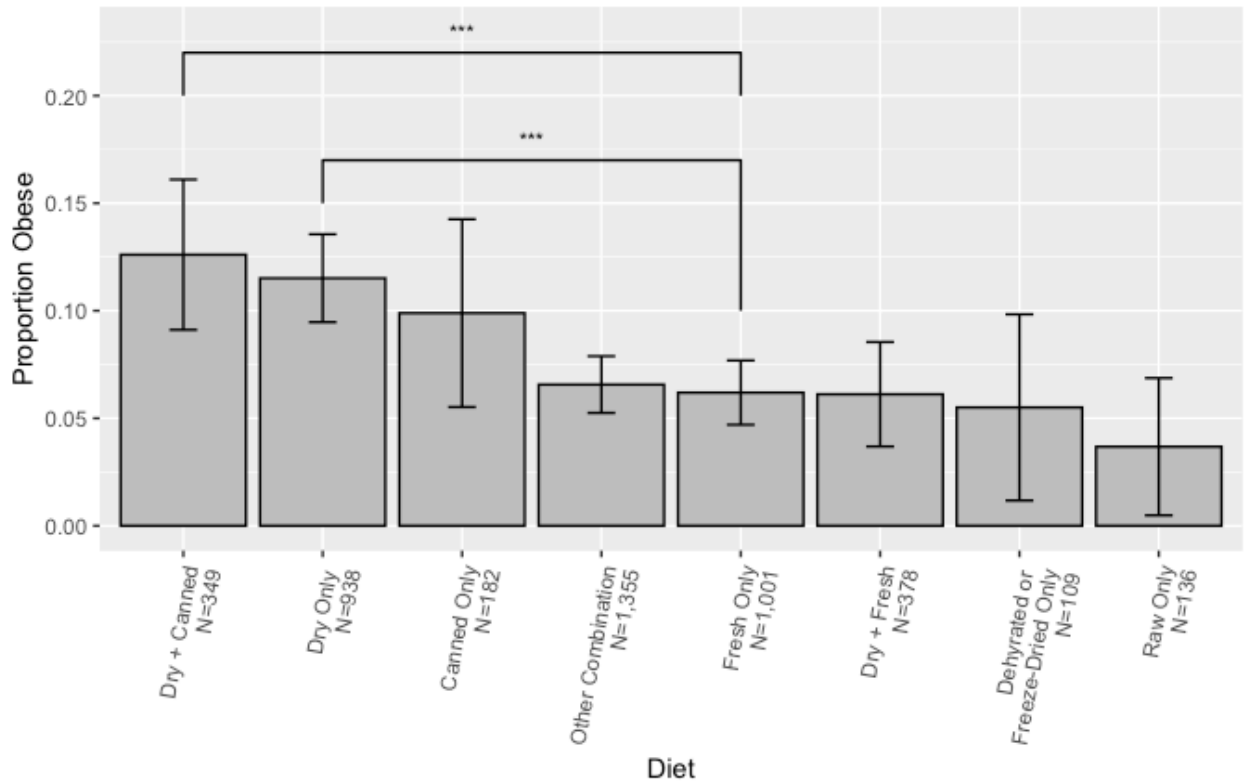
216 Title: Proportion of Dogs Overweight/Obese Relative to a Fresh Food Diet

217 Legend: Error bars show 95% confidence intervals. *, **, *** respectively represent $p < 0.05$,

218 $p < 0.01$, $p < 0.001$. “Other” includes any combination of reported dietary elements not represented

219 in the most common dietary configurations, for example having three or more regular dietary

220 elements.



221

222 Figure 3:

223 Title: Proportion of Dogs Obese Relative to a Fresh Food Diet

224 Legend: Error bars show 95% confidence intervals. *, **, *** respectively represent $p < 0.05$,

225 $p < 0.01$, $p < 0.001$. “Other” includes any combination of reported dietary elements not represented

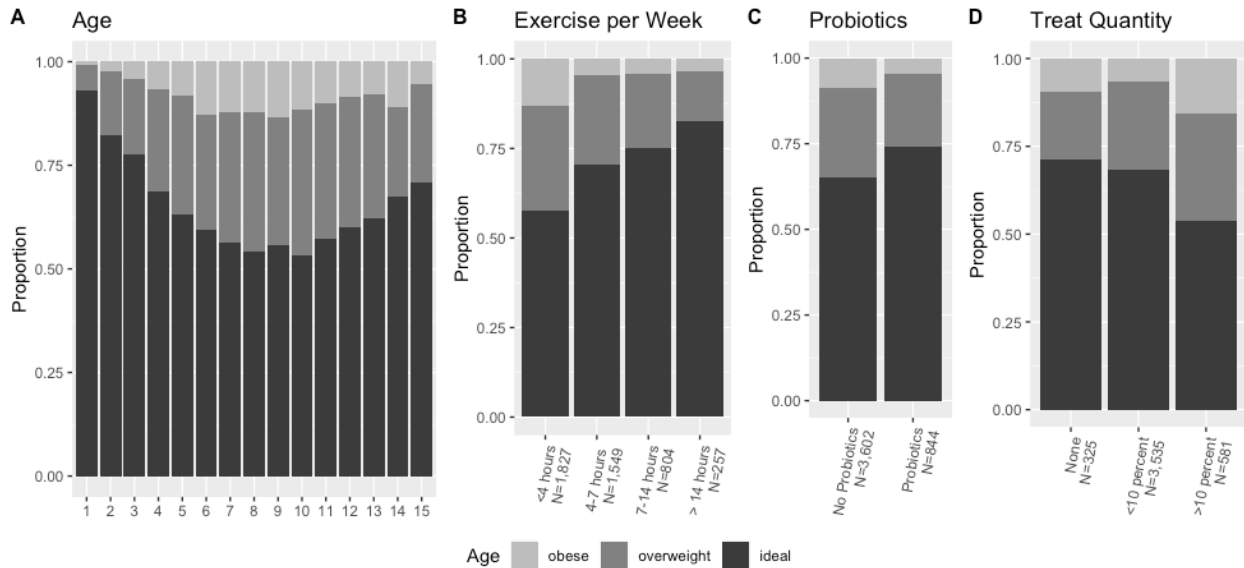
226 in the most common dietary configurations, for example having three or more regular dietary

227 elements.

228

229 Age:

230 Given the strong relationship between body condition and age in both the univariate and
231 multivariate models, we investigated this in further detail. We found that likelihood of
232 overweightness peaked around age 8-10, decreasing with further aging (Figure 4, A). Likelihood
233 of obesity alone showed a similar non-linear pattern. This relationship supports our use of
234 higher-order polynomial age terms in the logistic regression models.



235

236 Figure 4:

237 Title: Factors Influencing Body Condition Scores

238 Legend: Proportion of overweight and obese dogs by age (A), exercise per week (B), probiotic
239 consumption (C), and treat quantity (D).

240

241 Exercise:

242 Since exercise was shown to be statistically significant in both the univariate and multivariate
243 models ($p < 0.0001$), we further considered this relationship (Figure 4, B). We found that
244 incrementally increasing the amount of exercise per week decreased the likelihood of
245 overweightness/obesity. The same pattern holds for obesity.

246

247 Probiotics:

248 We also examined the relationship between probiotic supplementation and BCS (Figure 4, C).
249 In total, 844 dogs were currently taking probiotics, and respondents reported using a broad
250 range of commercial formulations. We found that probiotic supplementation was significant both
251 with respect to overweight/obese status (OR=0.65, $p<0.0001$) and obese status (OR=0.46,
252 $p<0.0001$) with dogs taking probiotics being more likely to be at an ideal weight.
253 Given that dogs receiving probiotics may be more likely to be at a lower weight due to having a
254 medical condition, we repeated this analysis using only the healthy cohort as previously defined
255 (N=3,173). We found a significant relationship with both overweight/obese status (OR=0.65,
256 $p<0.0001$) and obese status (OR=0.52, $p = 0.002$) in this cohort as well.

257
258 Since supplement usage may indicate increased owner health consciousness, we also
259 performed a similar test with the other supplements included in our analysis in order to
260 determine if this significant effect was specific to probiotics. We examined prebiotics (N=183),
261 multivitamins (N=425), CBD oil (N=540), fish oil (N=812), herbal supplements (N=207), and
262 immune support (N=121). None of these supplements showed a significant relationship with
263 either overweight/obese status or obese status in chi-square tests ($p>0.05$).

264
265 Treats:
266 Finally, we examined the univariate association between treat intake quantity (by percentage of
267 caloric needs being met by treats) and BCS (Figure 4, D). Both the univariate and multivariate
268 analyses confirmed that, while giving over 10% of a dog's diet in treats was associated with
269 higher BCS, there was no significant difference between giving under 10% of a dog's diet in
270 treats and abstaining completely, suggesting that giving treats in moderation is not a risk factor
271 for either overweightness or obesity.

272

273 Non-Significant Factors:

274 Given that some respondents (N=593) gave data for multiple dogs, and that joint households
275 may exhibited shared environmental factors not captured by existent survey questions, we
276 determined if there was a significant effect of household on reported body condition. We entered
277 household into the logistic regression model as a random effect, and an analysis of deviance
278 showed that it was not significant ($p>0.05$). Furthermore, given findings from other studies that
279 identified a relationship between sex and BCS (e.g. (6), or an significant interaction between sex
280 and neutered status on BCS (10), the analysis was repeated in the subset of animals for which
281 sex data were provided (N=3,922) but sex was not significant either as a main effect or in
282 interaction with neutering ($p>0.05$). Given previously reported overweightness rates of 52% and
283 41% for females and males respectively (5), and $\alpha=0.05$, we had $\beta>.99$ power to detect a main
284 effect, and following previously published guidelines for calculating power for interactions (16),
285 we calculated that we had $\beta>.90$ power to detect an interaction between sex and neutering.
286 Therefore, we are relatively confident in reporting that no relationship between sex and BCS
287 exists in this sample.

288

289 **Discussion:**

290 This study employed a cross-sectional direct-to-consumer data collection approach to identify
291 risk factors associated with increased owner-assessed body condition. Overweightness and
292 obesity were common issues in this population, with 33% of dogs reported as overweight/obese
293 and 8% reported as obese. This is comparable to the respective figures obtained in a study of
294 21,754 dogs in the United States wherein body condition scores were assessed by a
295 veterinarian (3). The large dataset assembled here allowed us to identify and then validate risk
296 factors using multiple approaches. Overweightness/obesity and obesity were each examined
297 through three logistic regression models, with variables chosen through stepwise selection,
298 Elastic Net selection, and an XGBoost machine learning model.

299

300 Many of the risk factors identified recapitulate robust findings from previous studies. Exercise
301 has previously been identified as protective against obesity (11,12,17). Neutering has also been
302 found to be a risk factor for overweightness but not obesity (6), and we find more significant
303 relationships with the combined overweightness/obesity models than with the models for obesity
304 alone. Though this result may be due to decreased power, this potential distinction in severity
305 may be important for dog owners to recognize when weighing the potential outcomes of
306 neutering. This relationship is corroborated by studies showing that neutering dogs results in
307 lower daily energy requirements combined with higher food consumption (18). Sex has
308 previously been found to be a risk factor both alone (6) and in interaction with neutering (10),
309 though other studies did not identify a significant effect (9). We specifically tested for an
310 association between sex and weight and, despite having adequate power, did not detect an
311 effect in our sample. While a number of studies (4,5,8) have reported increased age as a risk
312 factor for weight issues, we found in our sample that weight peaks around age 8-10 years, with
313 older animals less likely to be overweight or obese than their middle-aged counterparts. This
314 mirrors findings from other larger studies (3,5,6,9). This finding may reflect the decreased
315 lifespans of overweight and obese dogs.

316

317 One novel finding of our study is the association between increased BCS and the consumption
318 of dry food, which has previously been observed in cats (19,20) but not in dogs (3,11).
319 Specifically, we found that, compared to fresh food, dry food is significantly associated with
320 overweightness/obesity, both alone and in combination with canned or fresh food. Furthermore,
321 dry food only diets and dry plus canned combination diets were significantly associated with
322 obesity, but not dry plus fresh combination diets. This may indicate that supplementing with
323 other types of food ameliorates the more obesogenic consequences of certain diets. The
324 relationship between dry food and increased BCS may be partially due to the tendency of

325 owners to inaccurately measure dry food portions (21), which may be alleviated by the
326 decreased caloric density of fresh and raw foods. We posit that previous studies did not identify
327 a relationship between dry food and increased body weight due to the lack of fresh and raw
328 alternatives commercially available in past years. We also found that feeding commercial and
329 home-prepared fresh, frozen, and raw foods is associated with a lower likelihood of being
330 overweight or obese; however, diets containing raw animal products may contain higher rates of
331 bacterial contamination than other foods and may pose health risks to companion animals (22).
332 Observed differences in dietary factors could be due to a number of non-nutritional factors such
333 as the provided portion sizes, the individualized portioning of some fresh diets, or the higher
334 price point per calorie of some diets. Future studies should examine the effects of varied
335 proportions of these dietary elements and experimental dietary manipulation to determine the
336 direction of causality.

337

338 Another novel finding is that supplementation with probiotics is associated with being at an ideal
339 weight. This finding is specific to probiotics among other supplements reported in the survey,
340 and the effect persists in a sample composed of dogs without major reported health issues. This
341 relationship is supported by work that shows significant differences in the gut microbiota of
342 normal and obese dogs (23), as well as recent reviews and meta-analyses of experimental and
343 clinical trials of probiotic supplementation in different species (24–26). However, to the best of
344 our knowledge this is the first large cross-sectional demographic study that has specifically
345 identified probiotic supplementation as a potential protective factor with regard to
346 overweightness and obesity. The mechanisms behind this relationship are unclear, but in
347 addition to modulating energy harvest and nutrient absorption through alterations in microbiota,
348 probiotics might act through improving insulin sensitivity (27) or increasing satiety (24).
349 Additional prospective data should be collected to identify whether there is a causal relationship.

350

351 We also identified treat feeding practices as robust predictors of body condition. In contrast to
352 previous studies which identify even a moderate frequency of treat-feeding as a risk factor (8)
353 we find that feeding treats in moderation, i.e. with 10% or less of total caloric needs being met
354 by treats, is neither associated with overweightness/obesity nor obesity. This discordance
355 between findings may be due to differential effects of treat quantity and treat frequency.
356 However, these results should be interpreted cautiously as owner assessment of calories
357 provided by a given treat may often be imprecise.

358

359 The presence of other dogs has been previously studied as a risk factor for increased BCS, with
360 some studies identifying living in a single-dog household as a risk factor (11) and others finding
361 no significant relationship (5). We find that the presence of other dogs in the household is
362 associated with higher body weight, and we posit this may be due to the difficulty of
363 implementing food restriction in the presence of a dog of healthy weight that is being
364 concurrently fed.

365

366 Our models also included owner assessments of canine temperamental factors, including food
367 motivation level, pet appetite, and overall mood. Significant relationships between obesity and
368 temperamental factors such as appetite and food motivation have previously been identified
369 (12,28,29). It is possible that dogs that express higher food motivation and appetite receive
370 more calories from their owners, and food-seeking behavior may be associated with decreased
371 owner compliance with weight loss regimens. While dogs' subjective experience is difficult to
372 measure, owner-perceived emotional eating in dogs has been associated with owner-assessed
373 overall mood and anxiety (30). Tail-chasing, which emerged as a significant factor in some
374 models, may also be an index of behavioral issues (31). While the links between behavior,
375 mood, and obesity are unclear and likely to be multifactorial, serotonin has been implicated in

376 both mood and satiety (32) and serotonin-reuptake inhibitors have been shown to decrease tail-
377 chasing behavior (33).

378

379 Finally, we also note that our models identified additional variables, though it is difficult to
380 pinpoint the statistical reasons for these differences. We identified increased dental treatment
381 frequency as significant; however, the interpretation of this finding remains unclear. It is possible
382 that increased dental visit frequency reflects higher health consciousness in owners or more
383 frequent veterinary counseling on prevention of weight issues. A causal relationship between
384 periodontal inflammation and obesity seems unlikely, but there could be effects on the
385 microbiome or other processes that might contribute to adiposity. Some of our models also
386 identified a significant association between rural environments and increased BCS, which is
387 corroborated by previous studies (6,9).

388

389 Limitations of this investigation include the use of owner assessment of BCS and owner report
390 of other questionnaire items; prior studies have shown that owners inaccurately report body
391 condition (34). However, we validated the use of BCS in this sample by cross-referencing BCS
392 against owner-reported current-to-ideal body weight ratios and identified significant overlap as
393 detailed in Methods. Another shortcoming is that we did not solicit demographic or lifestyle data
394 of the owners, such as age and income, which have been previously shown to be associated
395 with canine weight issues (8). Another potential limitation of our findings is selection bias, as our
396 data were drawn primarily from the customer base of a pet health company providing
397 individually portioned fresh meals, which may be more health-conscious than the aggregate dog
398 owning population. However, this study is the first to report results from this unique population,
399 broadly in accord with previously reported risk factors, supporting the generalizability of these
400 findings. Finally, as the associations between the reported risk factors and BCS were cross-
401 sectional, temporality and causality were not addressed. Future studies should seek to

402 experimentally manipulate these risk factors individually or in combination to observe their
403 potentially synergistic effects on weight loss or maintenance, particularly diet, probiotics, and
404 treat quantity as they may be most easily manipulated by dog owners.

405

406 **Conclusions:**

407 In this cross-sectional, owner-reported study of 4,446 dogs, we identified risk factors for
408 overweightness and obesity using stepwise selection, and then confirmed these findings using
409 Elastic Net and XGBoost. Our findings recapitulated risk factors robustly identified by other
410 studies, including exercise, neutering, and a non-linear contribution of age. We also further
411 elucidated the contribution of previously studied risk factors; we identified dry food consumption,
412 excessive treat intake, and canine temperament as risk factors. Finally, we identified probiotic
413 supplementation as a potential protective factor. These findings are of clinical and practical
414 significance because the demographic factors identified may be used to proactively identify
415 dogs at increased risk for overweightness and obesity, and the lifestyle factors identified may
416 guide the development of interventions. Further studies employing experimental manipulations
417 are needed to establish whether these relationships are causal.

418

419 **Methods:**

420

421 *Data collection and selection procedures*

422 Customers of NomNomNow, a pet food and health company, were asked to complete a
423 comprehensive online health assessment for each pet in their care, composed of five broadly
424 targeted questionnaires containing questions about signalment, overall wellness, diet and
425 lifestyle, medical history, and product preferences. These included single-choice checkbox,
426 multiple-choice radio-button, dropdown, and fill-in-the-blank questions. We collected survey
427 responses from a total of 7,942 dogs of which 5,135 were complete. Dogs under one year of

428 age (N=415), pregnant or lactating dogs (N=4), and underweight dogs (N=272) were excluded
429 from the analysis, yielding a final sample of 4,446 dogs from 3,853 unique households broadly
430 distributed across the United States. A maximum of 122 questions were asked regarding each
431 dog, as some questions were served contingent upon responses to other questions. After
432 dummy-coding and grouping, there were 372 individual features, which were reduced to 47 after
433 removing variables related to medical conditions and treatment, product preferences, and highly
434 correlated or redundant questions. This initial exclusion step was performed because Monte
435 Carlo simulations show improved performance in stepwise models with fewer nuisance
436 variables (35). After further removing variables that were more than 5% incomplete, we were left
437 with 45 features which were used for subsequent analysis. The survey questions that
438 contributed to the final features are detailed in [Supplementary File 6].

439

440 Overweightness and Obesity

441

442 Weight status was assessed by dog owners using an image-based body condition score (BCS)
443 chart accompanied by a verbal description. BCS has been shown to be strongly correlated with
444 gold-standard dual-energy X-ray absorptiometry (DEXA) scans (36) and is regularly used both
445 by veterinarians and researchers for clinical assessment of overweightness and obesity.
446 Respondents were shown six options reflecting a nine point scale (BCS, Supplementary File 7
447 (13)). For the purposes of this analysis, we grouped the six pictures into four categories:
448 underweight (corresponding to BCS 3 or lower); ideal (corresponding to BCS 4-5); overweight
449 (corresponding to BCS 6); and obese (corresponding to BCS 7 or higher). Since owners have
450 been reported to systematically misperceive body condition scores (34) we validated these
451 scores against current and ideal body weights reported by a subset of respondents. Owner-
452 reported BCS showed strong correspondence with owner-reported current-to-ideal body weight
453 ratios. Using suggested ratio guidelines of >1.15 for overweightness and >1.30 for obesity (1)

454 we calculated sensitivity (the proportion of overweight dogs by weight ratio correctly selected as
455 overweight by BCS) and specificity (the proportion of ideal weight dogs by weight ratio correctly
456 selected as ideal by BCS). We calculated 90% sensitivity and 79% specificity for
457 overweightness/obesity, and 57% sensitivity and 94% specificity for obesity. Hence, dogs with
458 BCS ≥ 6 are referred to as “overweight” and those with BCS ≥ 7 as “obese.” For the survey
459 image for body condition shown to respondents see Supplementary File 7.

460

461 Diet

462 Owners were asked to check a box for each food type currently being fed, with multiple
463 selections allowed. The final binned categories consisted of canned food, dry food (kibble), raw
464 with home-prepared raw foods, dehydrated with freeze-dried foods, and commercial
465 fresh/frozen with home-cooked foods. The seven most common combinations of diets were
466 identified to be dry food only (N=938), canned food only (N=182), fresh food only (N=1,001), dry
467 plus canned food (N=349), dry plus fresh food (N=376), dehydrated/freeze-dried only (N=109),
468 raw only (N=136), and other configurations of these same elements (N=1,355); these diets were
469 coded as factors and entered into the model as such. We did not ask for proportions of these
470 dietary elements.

471

472 Subject Characteristics:

473 Out of a total of 4,446 dogs, 2,967 (67%) were at an ideal weight and 1,497 (33%) were
474 overweight or obese, of which 1,142 (25% of total) were overweight and 355 (8% of total) were
475 obese. In terms of sex, 1,727 (39%) were neutered male, 1,733 (39%) were neutered female,
476 262 (5.9%) were intact male, and 197 (4.4%) were intact female; 527 did not include both sex
477 and neutered status. The average age was 6.74 ± 4.09 years and the average weight was
478 13.6 ± 11.8 kg.

479

480 Data analysis

481 For each of the variable selection procedures, two models were run: the first to differentiate
482 ideal weight dogs from overweight and obese dogs, and the second to differentiate ideal weight
483 dogs from the smaller subset of dogs reported to be obese. The statistical significance for all
484 variable selection procedures was set at $\alpha=0.05$.

485 Univariate Analysis: Univariate associations between BCS and each of the 45 variables under
486 consideration were examined. We performed chi-square tests for binary variables, t-tests for
487 continuous variables, and ANOVA for categorical/ordinal variables, including arguably ordered
488 factors such as exercise and treats, due to the possibility of non-linear effects. We did not
489 correct for multiple comparisons in this analysis, in order to obtain a fuller, more descriptive,
490 model of potential associations.

491 Method 1: Logistic Regression with Stepwise Selection: A logistic model was fit using variables
492 selected through bidirectional stepwise selection using `StepAIC` in R. However, given the
493 statistical issues raised around traditional stepwise selection, including the use of Monte Carlo
494 simulations to show how infrequently all correct explanatory variables are selected during data
495 mining (35), two additional methods were used to identify ensembles of risk factors, which were
496 then entered into a traditional logistic regression to maximize interpretability.

497 Method 2: Elastic Net Selection: `ElasticNetCV` from the `sklearn` package was used to
498 select the parameters λ and α , which control the level of penalty and the relative ratio of L_1 and
499 L_2 penalties (39). Twenty iterations of Elastic Net were run using all variables, and the most
500 important variables selected by Elastic Net were used to fit a logistic regression model to
501 maximize interpretability. For both the overweight/obese and obese models, the best ensemble
502 of risk factors was selected by consecutively adding variables and performing ANOVAs with
503 significance tests to assess the contribution of each additional variable in the nested model,
504 continuing the process until reaching a variable that did not significantly improve the model.
505 Note that this differs from the true stepwise selection procedure performed before, in that the

506 variables are added in order of importance in the complete model, rather than by their additive
507 contribution to the partial model.

508 *Method 3: XGBoost Selection:* A grid search using `GridSearchCV()` was used to identify
509 parameter values. Twenty iterations of XGBoost were run using all variables, and variable
510 importance was averaged across iterations. The most important variables were entered
511 stepwise into a logistic regression model until subsequent entered variables failed to
512 significantly improve the predictive ability of the model as detailed for Elastic Net.

513 *Data Imputation:* Since not all survey questions were required, the 45 variables used in the
514 analysis had between 0-4.5% missing data, which were inferred via imputation using
515 `MissForest()` in R (40). Missingness and out-of-box imputation accuracy are provided for
516 each of the variables in [Supplementary File 8]. Variables with over 5% missingness were
517 excluded from analysis. Once variables were identified as important through the variable
518 selection methods delineated above, the final logistic regression model was fit using only
519 complete cases so as to avoid inaccurate or biased model fit values.

520 Univariate analysis, imputation, stepwise selection, and logistic regressions were conducted in
521 R version 3.5.2. Elastic Net and XGBoost were conducted in Python version 3.6.7.

522

523 **Declarations:**

524

525 *Ethics statement:*

526 This study was carried out in accordance with the recommendations of the Federal Policy for
527 the Protection of Human Subjects, U.S. Department of Health and Human Services. Since our
528 study gathered information from owners focused solely on their dogs it does not meet the
529 definition of human subjects research and therefore did not require review by an Institutional
530 Review Board.

531

532 Consent for publication:

533 Survey respondents agreed to a Terms of Service (TOS) consenting to using pet information for
534 research and publication. Furthermore, all the data in this study has been deidentified.

535

536 Availability of data and materials:

537 The deidentified datasets generated and/or analyzed during the current study are not publicly
538 available since they are generated for proprietary business and marketing purposes, but are
539 available from the corresponding author upon reasonable request.

540

541 Competing interests:

542 LP, JS, JT, DM, RH, and AJ received compensation from NomNomNow, Inc. during the
543 collection and publication of the data herein.

544

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549

550 Authors' contributions:

551 LP conceived the scope of the work, analyzed and interpreted the data, drafted the manuscript,
552 and created figures and tables. JS designed the survey questions and reviewed the findings and
553 manuscript. JT interpreted the data and critically reviewed the manuscript. DM implemented the
554 owner-reported assessment questions. RH conceived the scope of the work, designed the
555 survey questions, and reviewed the findings and the manuscript. AJ conceived the scope of the
556 work, interpreted the data, and reviewed the findings and the manuscript.

557

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562

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