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Early-life factors associated with all-cause mortality in UK Labrador Retrievers: analysis of the Dogslife longitudinal cohort

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Abstract

Domestic dogs provide valuable companionship and benefit human health and wellbeing. Advances in veterinary care have increased opportunities to manage disease and support healthy ageing. However, associations between mortality and many aspects of dogs' lifestyles and care remain poorly understood. Evidence linking diet and exercise to all-cause mortality in dogs is limited, while associations with neutering remain difficult to interpret because its timing is rarely considered.

Using data from Dogslife, a longitudinal cohort study of UK Labrador Retrievers, to investigate associations between characteristics measured during the first two years of life and subsequent all-cause mortality. Survival analyses included 2,540 dogs that survived to two years of age, of whom 888 reported deaths during follow-up. Higher mean body mass index between 12 and 24 months was associated with a higher hazard of death at age ten (Hazard ratio HR = 1.25, 95% confidence interval CI = 1.06–1.47). Reported consumption of raw food during the first two years (HR = 1.33, CI = 1.05–1.68), neutering before 448 days compared with later neutering or remaining entire (HR = 1.19, CI = 1.04–1.36), and male sex (HR = 1.18, CI = 1.03–1.36) were associated with a higher hazard of death.

Except for sex, these factors are potentially modifiable by owners and should be considered in the management of their dogs. Although these associations do not establish causality, they identify priorities for replication and targeted causal investigation, with the potential to inform future evidence-based guidance that supports healthy ageing and longevity in dogs.

Introduction

Understanding the factors that influence survival is important for developing interventions to support healthy ageing and longer lifespans. All-cause mortality allows investigation of risk factors on overall survival, rather than mortality attributed to specific diseases. In humans, it has been associated with a range of demographic, lifestyle, dietary, exercise and general health factors [1–3]. Yet in dogs, longevity research has focussed predominantly on associations with breed, sex, neutering, and obesity and some of the results are conflicting.

Sex and neutering have been inconsistently associated with lifespan [4–6] with interpretation complicated by the method of analysis, timing of neutering, potential differences in care provided between neutered and entire dogs, and a likely sex-specific impact of neutering [7–10]. Obesity and higher bodyweight have been associated with shortening lifespan and increasing risk of disease [11–13], although others found no association between bodyweight and mortality [14]. Better understanding of the relationship between neutering, obesity and lifespan is important because of the high prevalence of obesity among companion animals and is of particular significance to Labrador Retriever owners due to an apparent breed-predisposition for the condition [15, 16].

In contrast to humans, relatively few canine health studies have examined the potential associations with a broader range of modifiable risk factors associated with all-cause mortality, for example exercise, diet, and (owner) smoking [2, 17]. Physical activity is known to be associated with reduced all-cause mortality in

humans, compared to being inactive [18, 19], with evidence that benefits persist at high activity levels [20]. Physical activity is not commonly recorded in veterinary or insurance records and has rarely been included in studies of canine mortality. Evidence in dogs is therefore limited, with existing research principally examining associations between physical activity in later life and cognitive function rather than mortality [21]. A wide range of dietary factors have been linked to all-cause mortality in humans, e.g. caloric intake, fruit and vegetable intake or the consumption of specific diet types [2]. Yet evidence linking diet to lifespan or all-cause mortality in dogs has received comparatively little attention. Lifelong energy restriction has been shown to extend lifespan in Labrador Retrievers [22], while evidence concerning dietary composition or type is largely derived from retrospective owner surveys or therapeutic diets in studies of dogs with specific diseases [23, 24]

Dogslife was the first large-scale longitudinal study to collect repeated owner-reported data on the demographic characteristics, lifestyles, health and mortality of companion dogs through questionnaires offered throughout their lives [25, 26]. Dogslife collects phenotypic and health data that overlaps with that available from insurance and veterinary healthcare records, alongside factors not routinely captured by these sources including household characteristics, exercise, diet and non-prescription preventative healthcare [26]. Dogslife exclusively collects data on Labrador Retrievers, among the most popular dog breeds worldwide, and among the most commonly registered Royal Kennel Club breeds in the UK [27]. They have an intermediate lifespan relative to other dog breeds and deaths occur from a range of causes leading them to be good candidates for longitudinal all-cause mortality studies [28, 29]. Restriction to a single breed, although limiting external validity, reduces heterogeneity in morphology, skeletal size, genetic background and thus baseline mortality risk, facilitating investigation of demographic, lifestyle and physiological factors. This study aimed to use these longitudinal data to investigate associations between demographic, lifestyle and physiological factors and all-cause mortality in UK Labrador Retrievers.

Methods

Cohort and data collection

The Dogslife project is a longitudinal cohort study started in July 2010 by the Royal (Dick) Vet School at the University of Edinburgh. Owners of validated UK (now Royal) Kennel Club registered Labrador Retrievers submitted data about their pet's exercise, diet, general care, illnesses, preventative and therapeutic treatments in an online questionnaire. Owner demographics were defined at enrolment including household smoking status, household type and postcode. Owners are reminded to submit data monthly in the dog's first year of life and three-monthly thereafter, though submissions could occur at any timepoint. Owners are requested to inform the project if they can no longer participate in the study e.g. if their pet dies, is rehomed or if the owners move abroad, and give details in a free text box. Data were collected between 1st July 2010 and 23rd March 2026. Owners provided informed written consent to participate in the study through the study website registration. The Dogslife project received a favourable review from the University of Edinburgh Royal (Dick) School of Veterinary Studies Veterinary and Human Ethical Review Committees (ref: HERC_161_17 and VERC 11/12).

Owner demographics

Household type was defined as family (adult/s and children), more than one adult, retired (single or couple), or single adult. Owner postcode allowed classification into index of multiple deprivation (IMD) quintiles harmonised across the UK [30], using the English classification of IMD as most owners in the cohort lived in England [26].

Early-life analysis: eligibility

We elected to focus the analysis on risk factors in the first two years of life, as we had the most complete data for this period. To accurately represent early-life conditions (neuter status, exercise, body mass index - BMI), dogs were included in the early-life analysis if they had at least one survey before 365 days and at least one survey at or between 365–730 days. Dogs that died or were censored younger than the 'landmark' of 730 days were excluded as we could not assess early life risk factors sufficiently and to reduce the risk of immortal time bias. Questionnaire data submitted in the first 24 months of life was compressed to form composite variables to represent early-life experience. Diets were classified as wet or dry if they were always reported as such and mixed if both foods were reported. Free text was mined for reports of raw food and dogs were classified as having no reports of raw food or raw food reported once or more. Dogs were classified as having reported anthelmintic or flea treatment, being fed titbits, never or once or more. Missing entries for categorical data were filled with the nearest non-missing entry for each dog. If there were no entries for a question, categorical data were randomly assigned based on the population distribution for that question.

Estimating exercise duration

Categorical exercise durations (e.g. 1–5 minutes) were transformed to continuous variables by selecting a random value from a uniform distribution within the category. For the category 'over 2 hours', a top limit of three hours of exercise per day was assumed. Weighted averages for weekday and weekend exercise durations were summed to provide an estimate of minutes of per exercise week for each pair of related questions. Exercise was grouped into hours per week of total exercise, on lead (including running), off lead exercise, and activity involving fetching, chasing or retrieving (FCR activity). Preliminary inspection of exercise durations showed a steep increase over the first 24 months, then levelled off over the next ~ 12 months. As questionnaires were not submitted at fixed ages and comparing exercise duration at different time points could be misleading, we took the mean exercise duration for 0–365 days and 366–730 days. The mean performed as well or better than predicting exercise at 6 and 18 months using a generalised linear mixed model when tested on existing data.

Weight, height and body mass index

Weight was requested at every questionnaire, height at the withers was requested for the first 18 months. Records with implausible heights < 35 or > 75 cm (breed standard = 56cm; [31]) were removed and classed as missing. To impute missing weight and height data, non-linear mixed effects models with fixed effects

for sex and age and a random effect for individual dogs were used as previously described [32]. BMI was calculated by the standard formula:

$$BMI = \frac{weight\,(kg)}{height\ at\ shoulder\,(m)^2}$$

for dogs between 12 and 24 months, as data earlier than 12 months was highly variable and BMI may not be reliable in growing animals. Mean BMI was calculated where there were multiple data points between 12 and 24 months, if there was only one survey submitted then this BMI was taken. To evaluate risk factors for dog weight between 12 and 24 months, we used a generalised linear model including all relevant risk factors (coat colour, index of multiple deprivation, feeding of titbits, exposure to gonadal hormones < 448 days, raw diet, household type, diet type; Table 1) whilst controlling for sex and mean height (at 12–24 months). We used a backwards stepwise elimination approach, removing variables from a global model if they resulted in the same or lower Akaike's Information Criterion (AIC) value [33].

To assess the stability of BMI over time for dogs with weight measurements throughout life, we used a linear mixed model with an individual level random effect to explore associations between mean BMI in the 2nd year and mean BMI later in life (above 4 and 8 years) whilst accounting for age. We also used a generalised linear model with a binomial error distribution and logit link function to assess whether high BMI at 2 years was associated with high BMI after 8 years, with high BMI being classified as higher than or equal to the median BMI in the sample.

Neuter status

Dogs that are neutered before 6 or 12 months old may be at higher risk of joint disease later in life [34] and dogs neutered before the median age of neutering have been reported to have shorter lifespans [35]. The neuter status of some dogs past two years of age in our data was unknown (i.e. they were censored or we lacked questionnaire data between two years and death), and thus we could only classify dogs until the two-year point and could not model this variable in a linear manner. Therefore, we assessed the impact of gonadal exposure at four cutoffs; 6 months (182.5 days), 12 months (365 days), 448 days (median exposure to gonadal hormones, interquartile range = 289–987 days, n = 2540) and 24 months (730 days) to assess the relationship with lifespan. Neutering was defined as permanent surgical removal of gonads (ovaries or testes), thus chemical castration was not included. We used a Kaplan-Meier model to visualise time-to-neutering in the cohort, stratified by sex.

Reporting deaths and censoring

Survival time was defined as the time from birth to death. Though all lifespan estimates are based on assumed survival to two years of age, interpretation is simpler if models start at birth. Due to data collection sensitivities, some deaths or end of ownership reports were missing specific dates. If this was reported without a date within 365 days of the previous questionnaire submission, a date was randomly sampled from a uniform distribution between the last questionnaire and the reporting date. Where a death

or end of ownership was reported more than 365 days after the last questionnaire, we considered the uncertainty too high to estimate and the dog was censored at the most recent questionnaire submission.

Dogs that were rehomed or moved out of the UK during the study or explicitly left the study were censored at the time of reporting, and if the date was not exact, it was randomly sampled or censored using the same method as death dates. Dogs that had not reported a death or end of ownership were censored at the last known date they were alive, which was the most recent questionnaire submission. Of those that were censored in this way, lost to follow up (LTFU) was defined if the last submitted questionnaire was more than 730 days before the final study date (23rd March 2026) and administrative censoring was defined otherwise.

Survival analysis

Multivariable Cox-proportional hazards (PH) models were used to analyse the relationship between all-cause mortality and early-life risk factors, fitted using the 'survival' package in R [36]. Candidate variables for survival analysis including dog and owner details are listed in Table 1. The R package *ggsurvfit* was used for visualisation (ref).

Variable selection and merging

To avoid creating outliers and unstable variables (indicated by a high standard error to coefficient ratio), variables with very low frequencies in certain categories were either merged or excluded from the model. Low numbers in several variables were resolved by merging categories as follows: household type was merged into single adult and more than one adult; diet type (originally wet, dry, and mixed) was merged to 'only dry' and 'any wet reported'; index of multiple deprivation (IMD) was grouped into low (IMD 1, 2, and 3) and high (IMD 4 and 5); and coat colour was adjusted by merging fox red with yellow to align with Royal Kennel Club classifications (Table 1). If a variable lacked sufficient variation across the study population and could not be resolved by merging categories, it was excluded from the final model entirely.

Table 1

Candidate variables for survival analysis including for categorical variables; the total number of dogs for each value of a variable and the number and proportion of dogs that had died or been censored, and for continuous variables the overall median value and interquartile range and those values for the dogs that had died or been censored. Variables selected for the final model are shaded in grey.

Categorical variables

	Variable	Value	Number censored (%)	Number died (%)	Total
Dog characteristics	Season of birth	Autumn	322 (65.18%)	172 (34.82%)	494 (19.45%)
		Spring	490 (62.98%)	288 (37.02%)	778 (30.63%)
		Summer	476 (64.67%)	260 (35.33%)	736 (28.98%)
		Winter	362 (68.05%)	170 (31.95%)	532 (20.94%)
	Sex of dog	Female	854 (66.36%)	433 (33.64%)	1287 (50.67%)
		Male	796 (63.53%)	457 (36.47%)	1253 (49.33%)
	Coat colour	Black	869 (66.23%)	443 (33.77%)	1312 (51.65%)
		Chocolate	251 (58.1%)	181 (41.9%)	432 (17.01%)
		Fox red	98 (80.99%)	23 (19.01%)	121 (4.76%)
		Yellow	432 (64%)	243 (36%)	675 (26.57%)
	Coat colour: reduced	Black	869 (66.23%)	443 (33.77%)	1312 (51.65%)
		Chocolate	251 (58.1%)	181 (41.9%)	432 (17.01%)
		Yellow	530 (66.58%)	266 (33.42%)	796 (31.34%)
Dog lifestyle	Fed raw diet in first 2 years	No	1440 (64.52%)	792 (35.48%)	2232 (87.87%)
		Yes	210 (68.18%)	98 (31.82%)	308 (12.13%)
	Fed dry or wet food in first 2 years	Dry	876 (64.75%)	477 (35.25%)	1353 (53.27%)
		Mixed	732 (64.78%)	398 (35.22%)	1130 (44.49%)
		Wet	42 (73.68%)	15 (26.32%)	57 (2.24%)
	Fed dry or wet food in first 2 years: reduced	Any wet food	774 (65.21%)	413 (34.79%)	1187 (46.73%)
		Dry food only	876 (64.75%)	477 (35.25%)	1353 (53.27%)

Categorical variables

Variable	Value	Number censored (%)	Number died (%)	Total
Dog given titbits (treats) in first 2 years	No	68 (38.64%)	108 (61.36%)	176 (6.93%)
	Yes	1582 (66.92%)	782 (33.08%)	2364 (93.07%)
Parasite control (anti-parasitic or anthelmintic) in first 2 years	No	13 (65%)	7 (35%)	20 (0.79%)
	Yes	1637 (64.96%)	883 (35.04%)	2520 (99.21%)
Dog travelled abroad in first 2 years	No	1574 (64.85%)	853 (35.15%)	2427 (95.55%)
	Yes	76 (67.26%)	37 (32.74%)	113 (4.45%)
Neutered at > = 6m old	No	59 (54.63%)	49 (45.37%)	108 (4.25%)
	Yes	1591 (65.42%)	841 (34.58%)	2432 (95.75%)
Neutered at > = 12m old	No	437 (59.13%)	302 (40.87%)	739 (29.09%)
	Yes	1213 (67.35%)	588 (32.65%)	1801 (70.91%)
Neutered at > = 24m old	No	900 (62.37%)	543 (37.63%)	1443 (56.81%)
	Yes	750 (68.37%)	347 (31.63%)	1097 (43.19%)
Neutered at > = 448 days	No	631 (60.44%)	413 (39.56%)	1044 (41.1%)
	Yes	1019 (68.11%)	477 (31.89%)	1496 (58.9%)
Hours per week fetch/chase/retrieve (FCR) activity in 2nd year: categorical	0-89th percentile (< 5.82 hours per week)	1493 (65.2%)	797 (34.8%)	2290 (90.16%)
	90th percentile +(> = 5.82 hours per week)	157 (62.8%)	93 (37.2%)	250 (9.84%)
Hours per week FCR activity in 1st year: categorical	0-89th percentile (< 3.95 hours per week)	1497 (65.54%)	787 (34.46%)	2284 (89.92%)

Categorical variables					
	Variable	**Value**	**Number censored (%)**	**Number died (%)**	**Total**
		90th percentile +(> = 3.95 hours per week)	153 (59.77%)	103 (40.23%)	256 (10.08%)
Owner lifestyle	Smoker in household	No	1475 (65.27%)	785 (34.73%)	2260 (88.98%)
		Yes	175 (62.5%)	105 (37.5%)	280 (11.02%)
	Household type	Family (one or more adult and one or more children)	508 (64.14%)	284 (35.86%)	792 (31.18%)
		More than one adult	735 (63.31%)	426 (36.69%)	1161 (45.71%)
		Retired (single or couple)	255 (68.73%)	116 (31.27%)	371 (14.61%)
		Single adult	152 (70.37%)	64 (29.63%)	216 (8.5%)
	Index of multiple deprivation: categorised	Quintiles 1,2 and 3	1354 (64.75%)	737 (35.25%)	2091 (82.32%)
		Quintiles 4 and 5	296 (65.92%)	153 (34.08%)	449 (17.68%)
	Index of multiple deprivation	1 - least deprived	518 (65.32%)	275 (34.68%)	793 (31.22%)
		2	465 (63.7%)	265 (36.3%)	730 (28.74%)
		3	371 (65.32%)	197 (34.68%)	568 (22.36%)
		4	202 (64.54%)	111 (35.46%)	313 (12.32%)
		5 - most deprived	94 (69.12%)	42 (30.88%)	136 (5.35%)
Continuous variables					
			Median values (interquartile range)		
	Variable		**Censored**	**Died**	**Overall**

Categorical variables					
	Variable	**Value**	**Number censored (%)**	**Number died (%)**	**Total**
Dog lifestyle	Mean body mass index in 2nd year		86.58 (78.69–96.66)	88.88 (80.97–98.5)	87.51 (79.59–97.26)
	Mean hours per week of FCR activity in 1st year		1.35 (0.85–2.33)	1.51 (0.9–2.5)	1.4 (0.87–2.4)
	Mean hours per week of FCR activity in 2nd year		1.99 (1.13–3.34)	1.95 (1.15–3.27)	1.98 (1.13–3.32)
	Mean hours per week of total exercise in 1st year		13.79 (9.71–19.92)	14.44 (10.67–20.41)	14.01 (10.01–20.11)
	Mean hours per week of total exercise in 2nd year		18.62 (13.51–26.11)	18.04 (12.56–24.57)	18.41 (13.24–25.62)

To avoid collinearity, biologically and mathematically similar variables (such as total exercise versus FCR activity up to 12 and 24-months, and the different categories for duration of gonadal exposure) were not included in the multivariable model simultaneously. Instead, these competing variables were individually added to the model. The variable that resulted in the lowest AIC was then selected to represent that group (e.g., exercise, gonad exposure) in the final multivariable model [33]. Plausible interactions between risk factors were tested and included in the final model if they improved the AIC of the model.

Penalised spline univariable cox models were used to test for non-linear associations with mortality in continuous variables (exercise and BMI). Variables were tested for proportional hazards (PH) by visualising Schoenfeld residuals, univariable Kaplan Meier survival curves, and univariable cox proportional hazards models. The test for proportional hazards 'cox.zph' in the *survival* package [36] were utilised. Martingale residual plots were used to assess the functional form of continuous covariates and identify observations with poor model fit [37]. Influential observations were assessed using DFBETAs, which estimate the standardised change in each model coefficient when an observation is omitted [38]. Both residual types were calculated using the 'residuals.coxph' function in the *survival* package.

Informative censoring and sensitivity analysis

To check for informative censoring, we constructed high and low-risk Cox-PH models. In the high-risk model, LTFU individuals were assumed to die the day after censoring and in the low-risk model, LTFU individuals were assumed to live as long as the oldest individual that died in the study as outlined by [39]. Differences in the outputs of these sensitivity models compared to the full model are suggestive of informative censoring. To mitigate potential bias associated with informative censoring, Inverse Probability of Censoring Weighting (IPCW) was applied to the final Cox-PH model. We constructed a multivariable Cox-PH model to predict the risk of individuals being censored due to LTFU (not administrative censoring) including all covariates present in the final survival model – the 'Censoring model'. Household smoking

status violated the proportional hazards assumption and so was stratified to eliminate this assumption. We used the inverse predicted probabilities from this model to assign higher statistical weight to individuals that were atypical in their censor status, i.e., those who had a high probability of being censored but remained in the study and vice versa.

Calculating survival

A Kaplan-Meier model was used to estimate and visualise a survival curve stratified by sex. Median survival predictions based on the IPCW multivariable Cox-PH model were estimated for selected dog profiles and 95% confidence intervals were calculated as the 2.5th and 97.5th percentiles of the bootstrap-predicted survival probabilities. Uncertainty in the predicted survival was estimated using a non-parametric bootstrapping technique. In each bootstrap iteration, individuals from the main dataset are sampled with replacement, the censoring model is refitted, and weights are recalculated then used in the weighted Cox PH model, which captured the uncertainty in both the IPCW estimation and the survival model. All confidence intervals are reported at 95%.

Results

Study population

The Dogslife cohort contained valid questionnaire data on 7040 Labrador Retrievers, of which 6425 had submitted at least one questionnaire in the first 12 months of life and of those, 3068 had submitted at least one additional questionnaire between 12–24 months of age. We excluded 512 dogs that were censored before 730 days of age and 16 dogs that died before 730 days due to insufficient risk factor data, leaving 2540 dogs who were censored or died at more than 730 days of age and eligible for the study. Of the eligible dogs, 35.0% had been reported as died (n = 888) and 65.0% (n = 1650) were censored. Of those that died, 168 death dates were imputed. Of the censored dogs, 35.6% were still active in the study (n = 904, administrative censoring), 25.7% were lost to follow up (n = 652, more than 730 days between their last questionnaire and the study end), 0.9% had a death report with an unknown date that was reported more than 365 days after the last known alive date (n = 23), 0.7% had moved abroad (n = 18) and 2% had been rehomed (n = 53). The median age of entry into the study was 94 days (interquartile range (IQR) = 77–129 days). Not accounting for censoring, 84.9% of females and 64.0% of males in the study cohort were neutered before they either died or were censored. The median age of exposure to gonadal hormones for all cohort dogs was 448 days, whilst of the 74.6% of dogs that were reported to be neutered during the study, the median age of neutering was 420 days (IQR = 264–708 days, n = 1896). The majority of dogs were listed as being owned as pets (91.9%, n = 2333), 8.8% were listed as working (n = 223), 0.71% as assistance (n = 18), 0.51% as showing (n = 5), 0.20% as breeding (n = 5) and 0.12% as agility (n = 3). Fifty-six dogs had more than one option selected (0.02%), but no dogs were purely owned as breeding or agility dogs. Given survival until two years of age (due to the eligibility criteria for the study), the unadjusted median age of dogs at death was 11.65 years (4254 days, IQR = 9.66–13.02 years) and the unadjusted median age of dogs at censoring was 8.02 years (2929 days, IQR = 4.51–10.33 years).

Selected variables

Low numbers in preventative ectoparasite and endoparasite treatment and travel abroad in the first two years of life were excluded from the final model as they created unstable variables and/or outliers (Table 1). When comparing the co-linear exercise and gonadal hormone exposure variables, FCR activity between 12–24 months and gonad exposure cut off at the median age of neutering (448 days, unadjusted) produced the lowest AIC and were therefore selected for the final multivariable model. The median number of days threshold for gonadal hormone exposure gave the lowest AIC value so was selected for the final model, however AIC only changed by a maximum of seven between models (Table 2). When the six, twelve and twenty-four-month thresholds were included, none of those terms were significant in the model (Table 2).

Table 2
Estimates and confidence intervals and AIC values for four Cox-PH models with different time cutoffs for gonadal hormone exposure. The median value (448 days) was selected for inclusion in the final model due to that model having the lowest AIC value.

Cutoff threshold (days) included in model	Estimate of gonadal exposure (95% CI)	Standard error of estimate	AIC of model	Delta AIC
448	1.185 (1.036–1.355)	0.058	16266.62	0
730	0.902 (0.785–1.037)	0.060	16272.02	-5.4
183	0.797 (0.594–1.068)	0.128	16272.06	-5.43
365	0.927 (0.805–1.068)	0.062	16273.53	-6.91

Interactions between sex and coat colour, sex and neutering timing, and coat colour and mean BMI did not result in improvements in AIC and were not included in the final model. The linear predictor for BMI performed better than non-linear judged by visual inspection and AIC and so was selected. For exercise, the spline analysis suggested that hazard ratios were approximately constant up to ~ 2 hours/week, with a rising trend at higher exercise levels. To facilitate interpretation and account for this non-linear pattern, we categorised FCR activity at the 90th percentile: low (< 2.5 hours/week) and high (> 5 hours/week), with cut-points chosen based on the observed inflection point in the spline and the distribution of the data. Exposure to extreme FCR activity durations was correlated with exposure to extreme total exercise, since 85.5% (n = 2174) of dogs did not do either. Yet, dogs exposed to extreme FCR activity durations were equally as likely to be exposed to extreme total exercise (49.6%, n = 124) as not (50.4%, n = 126), showing the difference between the two measures.

During model assumption checks, Martingale residual plots showed that the initial Cox-PH model overpredicted the hazard of death in later life. Adding a smooth time-varying effect for mean BMI using a log(time) interaction centred at 10 years (as the functional form of this variable visually changed over time; Fig. S1) resolved these overpredictions and was therefore included in the final model (Fig. S2). The index of multiple deprivation (IMD) covariate showed a PH violation (p = 0.0012), but adding a smooth time-varying effect for this covariate introduced instability and did not improve model fit; therefore, IMD remained a time-fixed covariate (Table 1).

Survival analysis

The median survival time estimated by the Kaplan Meier null model, given survival up to two years old, was 12.7 years (95% confidence intervals (CI) = 12.5–12.8 years). The univariable analysis accounting for sex estimated median survival of 12.5 years for females (CI = 12.3–12.7 years) and 12.8 years for males (CI = 12.6–13.0 years; Fig. 1). Generalised Linear Models of censoring suggested informative censoring may be an issue in the data (Supplementary Materials – Censoring Analysis), therefore the IPCW-adjusted Cox-PH model outputs are the main results presented in the following text, though hazard ratios for all models are all provided (Fig. 2, Table 3, Table S1). In the IPCW-adjusted Cox-PH model survival estimates for selected dog profiles ranged from 11.8 to 13.21 years (Table S2). Male Labrador Retrievers had an 18.3% (3.4–35.5%) increased hazard of instantaneous death compared to females (Table 3 and Fig. 2). With variables fixed as the most common option and a low BMI of 73, this gives the median survival of male Labrador Retrievers as 12.96 years (CI = 12.72–13.24 years) compared to female Labrador Retrievers of 13.21 years (CI = 12.93–13.52 years; Fig. 3, Table S2), a difference of three months. Dogs with a 12–24-month mean BMI in the 90th percentile (over 109) were at 26.5% increased hazard of death at 10 years of age (standardised hazard ratio; 95% CI = 7.1–49.4%), compared to dogs with a mean BMI in the 10th percentile (less than 73; Fig. 4) at 2 years old. This was equivalent to a 0.66% increase in risk of hazard of death for every incremental increase in BMI (unstandardised hazard ratio; CI = 0.19–1.1%). Keeping all other variables fixed, for the typical female dog, the median survival with a BMI of 73 was 12.86 years (CI = 12.52–13.12 years) compared to 13.21 years for the same dog with a BMI of 109 (CI = 12.93–13.52 years), a difference of 0.35 years or around 4 months.

Figure 1. Survival curves for 1253 female and 1287 male Labrador Retrievers estimated with a Kaplan-Meier univariable model with sex as the covariate (male = blue, female = yellow line) with 95% confidence intervals (shaded areas). Sex-specific median survival is indicated with dashed grey lines.

Figure 2. Hazard ratios for multiple multivariable Cox proportional hazard (Cox PH) models including 2540 Labrador Retrievers. The ‘Censoring’ model estimated the hazard of being lost to follow-up (LTFU, n.b. administrative censoring and deaths are classed as ‘not censored’; orange) and four Cox-PH models estimated the hazard of death; the ‘Unweighted’ final model (blue), final model weighted by Inverse Probability of Censoring, ‘IPCW’ (yellow), ‘High risk’ (all LTFU dogs assumed to die the day after LTFU; red) and ‘Low risk’ (all LTFU dogs assumed to live until same age as longest-lived dog in study- 5755 days; green) models. Models share the same specifications except weighting and the censoring model does not include the time-varying effect for mean body mass index (BMI) over time. Mean BMI variables are expressed as a standardised hazard ratio interpreted as the hazard associated with a change from the 10th to the 90th percentile of BMI

Figure 3. Effect of changing mean BMI, gonadal hormone exposure time, sex and raw diet on median survival predicted from the multivariable Inverse Probability of Censoring-Weighted (IPCW) Cox-proportional hazards model. Left plot shows estimates based on a mean BMI of 73, right plot shows mean BMI of 109 with gonadal exposure as high (> = 448 days) or low (< 448 days) and whether the dog ate a raw diet in first 2 years of life. Points and error bars are coloured by sex (male – blue, female – yellow). All dog profiles are otherwise based on an average participant; a black coated Labrador with normal FCR activity

exercise levels (< 90th percentile), fed a dry, non-raw diet with titbits, in a non-smoking household with a IMD between 3 and 5.

Figure 4. Histogram of mean body mass index (BMI) for dogs from 12 to 24 months of age and mean weekly hours of fetching, chasing or retrieving activity between 12–24 months of age, stratified by sex (males = blue, females = yellow) for 2540 Labrador Retrievers. Vertical black dashed lines indicate the median, 10th and 90th percentiles of the full dataset where applicable.

Dogs that were neutered at less than or equal to 448 days (1.2 years old; unadjusted median gonadal hormone exposure time) were associated with an 18.5% increased hazard of death (CI = 3.6–35.5%) compared to dogs with exposure to gonadal hormones longer than 448 days. With all other variables fixed as previously described, female dogs with a mean BMI of 73 neutered below 448 days had a median survival of 12.95 years (CI = 12.72–13.24) compared to females neutered over 448 days with a median survival of 13.21 years (CI = 12.93–13.52), a difference of 0.26 years or around 3 months.

Eating a raw diet in the first 2 years of life was associated with a 33.7% increased hazard of death (CI = 5.9–68.9%). For average female dogs with a BMI of 73, this was associated with a difference in median survival of 0.4 years or almost 5 months (no raw = 13.21 years, CI = 12.93–13.52, c.f. raw = 12.81 years, CI = 12.37–13.25).

Dogs that played over 5.8 hours of FCR activity per week between one and two years old (in the highest 10th percentile) were weakly associated with an increased hazard of death in the unweighted model compared to dogs exposed to FCR activity for much less than 5.8 hours per week (HR = 1.25, CI = 1.01–1.56) but this was not statistically significant in the IPCW model (HR = 1.24, CI = 0.99–1.54).

Table 3

Hazard ratios for the multivariable Inverse Probability Censored Weighted and unweighted cox PH model with a time-varying effect for mean BMI (centred at 10 years). The effect of mean BMI has been adjusted to represent the effect associated with the difference between the 10th and 90th percentile of BMI (Fig. 4).

Variable	**IPCW weighted**			**Unweighted**		
	Hazard ratio (95% CI)	**Standard error**	**Statistic**	**Hazard ratio (95% CI)**	**Standard error**	**Statistic**
Sex: female	Baseline					
Sex: Male	**1.183 (1.034–1.355)**	**0.058**	**2.44**	**1.186 (1.037–1.356)**	**0.068**	**2.496**
Colour: Black	Baseline					
Colour: Chocolate	0.961 (0.804–1.149)	0.076	-0.437	0.98 (0.82–1.17)	0.09	-0.228
Colour: Yellow	1.149 (0.986–1.34)	0.067	1.776	1.14 (0.978–1.328)	0.078	1.679
No smoking in household	Baseline					
Smoking in household	1.108 (0.899–1.364)	0.087	0.961	1.079 (0.877–1.327)	0.106	0.716
Titbits not given	Baseline					
Titbits given	1.157 (0.94–1.425)	0.09	1.376	1.13 (0.918–1.39)	0.106	1.153
Diet type: any wet food	Baseline					
Diet type: Dry food only	1.113 (0.961–1.289)	0.063	1.433	1.11 (0.96–1.283)	0.074	1.405
No raw food	Baseline					
Raw diet	**1.337 (1.059–1.689)**	**0.102**	**2.437**	**1.333 (1.059–1.678)**	**0.117**	**2.445**
IMD category 1–3 (least deprived)	Baseline					
IMD category 4–5 (most deprived)	1.051 (0.88–1.255)	0.073	0.552	1.048 (0.878–1.25)	0.09	0.517

Variable	IPCW weighted			Unweighted		
	Hazard ratio (95% CI)	**Standard error**	**Statistic**	**Hazard ratio (95% CI)**	**Standard error**	**Statistic**
Gonadal exposure long (> 448 days)	Baseline					
Gonadal exposure short (< = 448 days)	**1.185 (1.036–1.355)**	**0.058**	**2.474**	**1.194 (1.044–1.366)**	**0.069**	**2.588**
Mean BMI in 2nd yr at 10 yrs (standardised hazard ratio)	**1.265 (1.071–1.494)**	**0.002**	**2.768**	**1.266 (1.079–1.484)**	**0.002**	**2.899**
Mean BMI in 2nd yr over time (standardised hazard ratio)	1.191 (0.802–1.771)	0.006	0.866	1.169 (0.754–1.812)	0.006	0.697
Extreme fetch in 2nd yr (0-90th PC)	Baseline					
Extreme fetch in 2nd yr (> 90th PC)	1.238 (0.994–1.54)	0.092	1.909	**1.253 (1.008–1.557)**	**0.111**	**2.036**

Weight and BMI over time

The mean weight of the study dogs between 12 and 24 months old was 28.56 kg (SD = 4.9 kg) and mean height was 56.60 cm (SD = 4.19 cm), resulting in a mean BMI of 89.85 (SD = 16.78). The relationship between height, weight and BMI can be visualised in Figure S3. For an otherwise similar Labrador, male Labradors had an estimated mean weight of 3.97 kg more than female Labradors (CI = 3.62–4.32 kg; Table S3, Fig. 5). In this model, coat colour with fox red as a category did not cause problems so was included. Compared to black Labradors, fox red Labradors were significantly lighter (-0.87, CI = -1.6 – -0.14), whereas yellow were 0.53 kg heavier (CI = 0.17–0.9 kg) and chocolate Labradors had an estimated mean weight 1.8 kg heavier (CI = 1.37–2.23 kg), where all other factors were fixed. Labradors fed only dry food in the first two years were 0.58 kg lighter (CI = -0.92– -0.25 kg). Compared to living in the most affluent areas, dogs living in the most deprived areas (IMD categories 5 and 6) had higher weights (1.1 kg, CI = 0.59–1.62 kg and 1.61 kg, CI = 0.89–2.33 kg). Mean height was associated with mean weight (0.3 kg, CI = 0.26–0.34 kg). Mean weight was not significantly associated with total exercise duration between 12–24 months or being fed raw food in the first two years of life.

Figure 5. Mean weights and heights of 2540 Labrador Retrievers between 12 and 24 months old. Points show actual data points and lines and shaded areas show multivariate linear model predictions and 95% confidence intervals stratified by coat colour and split by sex (males left, females right). Fixed model variables for predictions were index of multiple deprivation category 1 (least deprived), mean total exercise per week (18.4 hours), no raw food and fed wet food in first two years of life.

For a subset of dogs with questionnaires submitted over 8 years old, mean BMI at two years was significantly associated with BMI over four years of age (estimate = 0.92, CI = 0.89–0.96, conditional R^2 = 0.91, marginal R^2 = 0.64, n = 1105) and over eight years of age (estimate = 0.97, CI = 0.92–1.03, conditional R^2 = 0.93, marginal R^2 = 0.62, n = 611), whilst accounting for age at measurement and repeated observations within dogs. The median mean BMI of dogs in their second year of life was 87.5 and the median mean BMI over eight years was 94.3. Among dogs with high BMI (more than median) in the second year of life, the predicted probability of high BMI (more than median) after eight years was 79.7% (CI 74.9–83.9%). Among dogs with low BMI at two years, the predicted probability of a high BMI after eight years was 20.3% (CI 16.2–25.2%).

Timing of neutering

The Kaplan-Meier analysis, which accounted for censored individuals, calculated the median age of neutering females as 484 days (1.3 years, CI = 461–516 days). This was significantly earlier than males at 726 days (2.0 years, CI = 639–874 days; Fig. S4). Females were more likely to be neutered than males, with the probability of being neutered by four years old 73.3% for females (CI = 70.8–75.7%) and 59.4% for males (CI = 56.5–62.0%). By ten years old, the probability of being neutered for females was 90.4% (CI = 88.3–92.2%) and 66.6% for males (CI = 63.7–69.4%; Fig. S4). Most neutering occurred between 2011 and 2018, with 8–12% of neuters occurring annually during this period, other years ranged from 0–4% annual neuters.

Discussion

Lifestyle factors in the first two years of life were associated with lifespan in Labrador Retrievers in this study. A higher mean BMI and feeding of raw food in the first two years of life, being male and being neutered before the median age of neutering (448 days) were associated with reduced lifespan. Overall, these variables were associated with differences in median survival on the scale of months rather than years. However, excluding sex, these lifestyle factors are amenable to change and therefore represent valuable opportunities to maximise Labrador lifespan, starting as early as the first two years of life. We found a weak association between extreme number of hours of FCR activity in the second year of life and risk of death in the unweighted model, but this was not significant in the IPCW-adjusted model. Contrary to other research, there was no association between index of multiple deprivation and risk of death.

Lifespan

The median lifespan estimate of 12.7 years is very similar to previous estimates of UK Labrador lifespan, being very close to the original median in show dogs of 12.6 years (Michell in 1999) and similar to median survival of 12 [6] and 12.5 years [28] and a life expectancy at birth of 11.77 years [40], all using VetCompass data based on veterinary records. Despite two studies solely including Kennel Club-registered Labradors, our value is slightly higher than Lewis's estimate of 11.5 years [41] and higher than all the aforementioned UK-based studies. This may be influenced by our assumption of survival until two years of age, to facilitate estimation of risk factors. We did not expect this to have a large impact due to low mortality in this age of

dog; only 16 dogs in the cohort (0.52%) died before two years of age, and a large observational study showed that the probability of dogs dying in the first and second year of life was 0.007 and 0.009 respectively [40]. All data sources, including our own are likely to have bias and limitations. Veterinary healthcare records are likely to miss dogs not under veterinary care, dogs that died at home or unreported deaths. Retrospective studies are susceptible to recall bias, while voluntary recruitment and the requirement for repeated questionnaire completion may have resulted in participation and retention bias in the Dogslife cohort, potentially favouring owners who were particularly willing to engage in long-term canine health research [26]. Despite this, the similarity of the estimates suggests that each source of data is useful and methods were robust.

The raw Dogslife data showed a median age of death of dogs that had died in the study of 11.7 years, a year less than the adjust survival analysis median lifespan of 12.7 years. This demonstrates the importance of using survival analysis techniques which include censored individuals to more accurately assess lifespan. This is particularly crucial in ongoing cohort studies to account for dogs still active in the cohort, whom may be likely to be longer-lived, especially if most of the cohort were enrolled in early years of the study, as is the case in Dogslife.

Neutering and sex

Our final model found that neutering before 448 days (the median age of neutering) was associated with a higher hazard of death compared with being neutered on or after 448 days or remaining entire. Few other studies have directly examined neutering in relation to longevity. Three Labrador-specific studies explored related factors, with contrasting findings. Neutered Labradors in a UK primary-care population had a greater median longevity than entire Labradors, though age at neutering was not considered and the comparison was unadjusted for confounding factors [6]. Another study associated neutering male Labradors at less than six months with increased joint conditions, and neutering females between 2 and 8 years with increased risk of haemangiosarcoma, lymphosarcoma and mast cell tumours [8], conditions which could contribute to all-cause mortality. Lastly, age at neutering was not associated with longevity in a small cohort of Labrador Retrievers, though all were neutered relatively late in life (median age at neutering = 5.5 years). In two all-breed analyses using US and UK veterinary databases, neutering was found to be associated with decreased hazard of death, greater than the association with sex in the US analysis [42]. A beneficial effect of neutering was found in an all-breed study of Italian dogs [4] and in another analysis with data taken from the same UK VetCompass dataset which found that neutered dogs had greater life expectancies than their entire counterparts [40]. In all the previously mentioned studies except the Hart study, dogs were dichotomously classified as neutered or entire and without accounting for age at neutering. As neutering probability increases with age, neutered dogs must survive long enough to undergo the procedure. Analyses that do not account for its timing may therefore be susceptible to immortal time bias, potentially contributing to an apparent survival advantage among neutered dogs [7]. To reduce this potential bias in the present study, dogs were eligible only if they had survived or remained in the study to at least two years old, and only neutering thresholds below 730 days were examined. Although this limited our ability to examine neutering occurring over 730 days, all included dogs (neutered or not) had survived beyond the thresholds used to classify gonadal hormone exposure and immortal time bias was mitigated.

Male sex was associated with a higher hazard of death, as has been found in other studies in Labrador Retrievers, other dog breeds and many other species, including humans [4, 40, 43]. However, greater lifespan has also been associated with neutered and entire males compared to entire females [28]. Proposed explanations for sex differences in lifespan include sex-specific hormonal effects (e.g. the protective effect of oestrogen) and sex-chromosomal-linked mechanisms [44]. Although Hoffman et al. (2018) concluded that sex played a relatively minor role compared with neutering, our findings suggest that sex may remain independently relevant when the timing of neutering is considered, aligning with the current view that both mechanisms influence sex-differences in lifespan [44]. Though differences in the study populations and classification of neutering may have contributed to the different findings.

Breed-specific studies or accounting for breed and sex is crucial for interpreting analyses of neutering and survival due to the breed- and sex-specific nature of both lifespan and of timing and effects of neutering, for example comparisons between closely related Golden Retrievers and Labrador Retrievers showed substantial breed and sex differences when exploring the relationship between neutering and joint conditions and neoplasia [8].

Our findings are the first Labrador Retriever-specific evaluation of the association between neutering and survival and showed an increased hazard of death associated with neutering below 448 days, whilst accounting for sex and considering age of neutering. Yet, we do not suggest this provides definitive conclusions on which to base recommendations. Firstly, when very similar thresholds for classifying timing of neutering were tested (6,12,24 months), they did not result in statistically significant associations with mortality, suggesting that our finding may not be robust to methodological or sample differences. Secondly, our findings did not evaluate differences between neutering after 24 months or never neutering. We suggest that further, more targeted investigation is warranted to decipher the complex effects of this commonly performed elective procedure.

There were some differences between the Dogslife cohort and other published neutering data. A higher overall proportion of dogs in this study cohort were neutered, 84.9% of females and 64.0% of males (overall 75%) compared to for example, 59.7% of females and 54.8% of males in a UK primary-care dataset [6] or 57.4% of all dogs neutered in an all-breed sample of the same dataset [40]. This may reflect the participation bias and socioeconomic status of the owners in Dogslife. The median age of neutered dogs was 1.3 years for females and two years for males, with most neuters occurring between 2011–2018. Earlier neutering for females may reflect the inconvenience of behaviour-change and symptoms of oestrus and a desire to eliminate the risk of unintended mating, however it is the opposite of guidance which generally suggests females benefit from later neutering compared to males. Overall, age of neutering was later than typical UK veterinary advice for all breeds collated in 2008 of 6.5 months for females and 7.5 months for males [45], but more in line with later breed-specific guidance based on minimising the risk of neutering-associated health conditions (e.g. joint disorders, cancers, pyometra) which suggested that Labradors should not be neutered before 6 months if male and 12 months if female [34]. This may reflect the developing focus on not only the effects of neutering, but the length of time dogs are exposed to gonadal hormones [9, 46].

Body mass index

We found increased BMI in the second year of life was associated with an increased hazard of death at age ten. This reflects existing experimental literature where kennelled Labrador puppies fed ad libitum (and thus had a higher BMI) from eight weeks of age had shortened median lifespans compared to dogs fed 25% less than their counterparts [22, 47, 48]. Those dogs were more likely to develop hip dysplasia and had a shorter time to onset of chronic diseases, suggesting that these conditions may play a role in shortening lifespan. Another small longitudinal study of 39 Labradors, showed increased body weight at the age of ten years was associated with increased hazard of death [11]. Our study specifically assessed the association between early BMI and all-cause mortality, yet early life BMI may act as a proxy for later life BMI. In a subset of Dogslife dogs that participated in the study for over five years, there was a strong association between BMI at two years and mean BMI over five and eight years, suggesting that dogs' BMI may be determined early in life, with the caveat that this subset might not be fully representative of the cohort. Whilst dogs with a higher BMI at two years of age were 80% likely to have a high BMI over eight years, this was not inevitable and 20% of Labradors with a high BMI at two went on to have a low BMI in later life. This demonstrates that whilst BMI is most likely to track throughout life, there are opportunities for change, as was seen in human adolescents who increased their leisure activity [49].

Data from US veterinary hospitals demonstrated that being an overweight Labrador in middle age (6.5–8.5 years) was associated with an increased hazard of death (hazard ratio = 1.83, 95% CI = 1.54–2.17, n = 11867) [13]. The proportional reduction in lifespan was around 4% in Labradors, which is similar to the 3% difference associated with going from a low to high BMI in our study, and comparably less than reductions reported in other, typically smaller breeds where, for example, the maximum reduction in lifespan was 15% for Yorkshire Terriers [13].

A limitation of owner-derived data is the lack of an objective body condition score to suggest obesity. In our study, BMI accounted for differences in height and the single-breed nature of the study limited any morphological differences that might skew BMI differences. Analyses were anchored by differences in BMI relative to the cohort (e.g. lower or higher than the median BMI), rather than absolute values (e.g. in humans a value of over 30 is defined as obesity), therefore results can be interpreted as relative to the average Labrador in our cohort. The mean weight of the 1–2 year-old dogs in our study was lower than the mean adult weight of Labradors in a VetCompass study (28.6 c.f. 33.0 kg) but similar to their median estimates of bodyweight at two years old, which is expected given that weight increased up until about 5 years old [6]. This suggests that weights in the Dogslife cohort are not dissimilar to the general UK Labrador population. Obesity in companion animals is a common and complex issue that can cause multiple health problems in dogs including metabolic disorders, orthopaedic conditions and cardiac disease [50] and has also been described as a One Health issue as pet obesity may be associated with overweight humans [51]. Our finding is of particular importance to Labradors and their owners as Labradors may be at a higher risk of obesity than other breeds [52], partly due to genetic factors such as the pro-opiomelanocortin (POM-C) gene deletion identified in some dogs [53]. Although weight-loss is achievable and can result in improved quality of life [54], many veterinary-led weight loss programmes are unsuccessful [55] and focus should be placed on prevention rather than treatment. We suggest that early

awareness of weight management and intervention may be particularly beneficial, and that veterinary professionals should help facilitate this.

We found no association between coat colour and lifespan in the multivariable analysis, in contrast to a previous univariable analysis that identified a higher risk of death among chocolate Labrador Retrievers [6]. Chocolate coloured coat has also been associated with heavier dogs in the Dogslife cohort [56], and with obesity in another cohort of British Labrador Retrievers [57], raising the possibility that any association between coat colour and mortality might be mediated or confounded by BMI. However, removing BMI from the multivariable model and examining coat colour in a univariable analysis did not materially alter the hazard estimates. Therefore, adjustment for BMI does not appear to explain the absence of an association in the present study.

Diet

The majority of our dogs ate dry food only and this was not associated with a difference in hazard of death. Diet has been clearly associated with lifespan in human studies [1], however the distinction between dry and wet food may not sufficiently capture many nutritional parameters that may be associated with lifespan.

We found that reported consumption of raw food during the first two years of life was associated with a higher hazard of death. We do not know whether these dogs continued to eat raw food subsequently. The exposure may therefore represent either raw feeding during early life or a proxy for a broader pattern of raw feeding throughout life. To our knowledge, this association has not previously been tested at a population level in dogs. In our study, residual confounding is possible as raw-feeding owners may differ from others in various aspects such as veterinary engagement or other health-management practices. In addition, reverse causation is possible as we did not record if the diet was changed in response to an existing health condition.

Related observational studies examining raw diets have provided contrasting results. A cross-sectional analysis by the Dog Aging Project found that commercial raw diets were associated with higher odds of owner-reported respiratory disease, although temporal order of diet and disease could not be established [58]. Conversely, two Finnish observational studies associated non-processed meat-based diets with a lower subsequent occurrence of chronic enteropathy and allergy or atopy [59, 60]. These studies examined particular health conditions rather than mortality and are subject to many of the same limitations as the present analysis.

We could not consistently distinguish between commercial and homemade raw food. This is important because homemade diets may be more likely to be nutritionally unbalanced, whereas appropriately formulated commercial diets may be nutritionally complete [61, 62]. Raw diets may also expose dogs to bacterial pathogens and antimicrobial-resistant bacteria [63, 64]. These findings identify possible hazards of some raw diets but only offer hypotheses for the association with mortality observed in our study. Further longitudinal research using more detailed dietary measurements is required to determine whether raw feeding is causally associated with mortality and whether any association differs according to the type

of raw diet and particularly identifying the importance of the duration and timing of raw feeding in early life when the dog's microbiome is still developing [65]

Exercise

Including FCR activity in the second year of life improved the performance of multivariable models more than FCR activity in the first year of life and total exercise in the first or second year, therefore this was the exercise variable included in the final model. Dogs in the highest decile of FCR activity duration (> = 5.81 hours per week) were associated with a higher hazard of death in both the unweighted and IPCW models. However, in the IPCW-adjusted model, the confidence interval included the null value and the association was no longer statistically significant.

General exercise may help maintain lean body mass in Labradors [12] and is associated with a healthier aging and longer lifespan in humans [18–20]. However, FCR activity differs from general physical activity because it involves repeated acceleration, braking and rapid changes of direction, potentially exposing the joints to high-impact, torsional and shear forces. A small (n = 160) retrospective case-control study found that chasing balls or sticks was associated with increased odds of being identified with hip dysplasia and elbow arthrosis in Swedish Labrador Retrievers, though genetic factors were not included in the analysis [66]. In a prospective study including 133 Norwegian Labrador Retrievers that accounted for similarities among littermates, daily use of stairs from birth to three months was associated with increased risk of hip dysplasia, yet off-leash exercise during this period was protective; exercise between three and twelve months was not associated with hip dysplasia [67].

These findings suggest that associations with musculoskeletal health may depend on the type, intensity and developmental timing of exercise. However, the present analysis did not examine injuries or musculoskeletal disease and therefore cannot establish why prolonged FCR activity may be associated with mortality. Musculoskeletal disorders are a common cause of mortality in Labrador Retrievers, accounting for 24.5% of deaths in a VetCompass study [6] and whilst they did not appear to shorten lifespan, they are likely to compromise the quality of life for the dog and reduce healthspan. Further investigation is therefore warranted to determine whether this finding is reproducible and evaluate the relationship with musculoskeletal disorders.

Index of multiple deprivation

There was no significant association between lifespan and the deprivation level of where the dog lived, which contrasts with an all-breed study, which found that higher levels of deprivation were linked to premature mortality in dogs and cats [68]. This may be due to insufficient sample size, as only 18% of dogs in this study were in the lower two brackets of deprivation indices. As we found higher bodyweight was associated with lower deprivation indices, there may be mediatory effects of BMI, which was included in the present analysis, but not in the Farrell et al. analysis.

Strengths, limitations and future work

A major strength of Dogslife is its longitudinal collection of repeated demographic, lifestyle and health data from early life. The relatively short canine lifespan also allowed follow-up across a substantial proportion of the life course, which is rarely feasible in human cohort studies. Alongside their exposure to many of the same environmental influences as humans, this supports the value of dogs as a comparative model of ageing [69]. Identifying potentially modifiable factors associated with canine mortality may therefore help inform interventions to support healthy ageing in dogs while generating priorities for future comparative research.

Some participants were more likely than others to drop out of the study. Participants from households where smoking was reported, those living in more deprived areas, and those whose dogs had a higher mean BMI or more than 448 days of gonadal hormone exposure were more likely to drop out. As several of these characteristics may also be linked to mortality, drop-out may have biased the unweighted analysis. We used inverse probability of censoring weights to reduce this potential bias by giving more weight to dogs that remained in the study but had characteristics associated with drop-out. However, this method only accounts for factors that were measured and included in the model and bias from unmeasured factors linked to both drop-out and mortality may remain. Nevertheless, the broad consistency of estimates between the unweighted and IPCW-adjusted analyses suggests that differential drop-out did not substantially alter most of our main findings, although the weaker evidence for the association with FCR activity after IPCW adjustment indicates that some estimates may have been affected.

This study concurrently investigated a broad range of potential risk factors but due to the study design and analytical framework we were unable to indicate causality in specific relationships. Future work will use specific hypotheses generated from this dataset to define and estimate causal effects using targeted learning approaches, subject to the required causal assumptions (van der Laan and Rose, 2011; Schuler and Rose, 2017).

Conclusion

This analysis of the Dogslife cohort has enabled simultaneous evaluation of demographic, lifestyle, dietary and exercise factors associated with all-cause mortality in Labrador Retrievers. Associations between characteristics measured in early life, including BMI, raw feeding, neutering before 448 days and subsequent mortality highlight puppyhood as a potentially important period for establishing behaviours and management practices that may influence later survival. Although these associations are observational, they identify priorities for targeted research to determine whether these relationships are causal. Overall, these findings demonstrate the value of longitudinal cohort data for understanding canine survival and identify potentially modifiable factors that warrant further investigation and may inform evidence-based guidance to support healthy ageing in dogs.

Declarations

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Data availability statement

Anonymous data used for the present analysis and R code used in analysis will be available on publication at University of Edinburgh Datashare. Code and the data dictionary are publicly available for reviewers at https://github.com/fieldingh/Dogslife_AllCauseMortality.git , though this is not anonymous.

Supporting information

S1 Appendix. Contains supplementary methods, results, tables (Tables S1-S3) and figures (Figures S1-S4).

References

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Figures

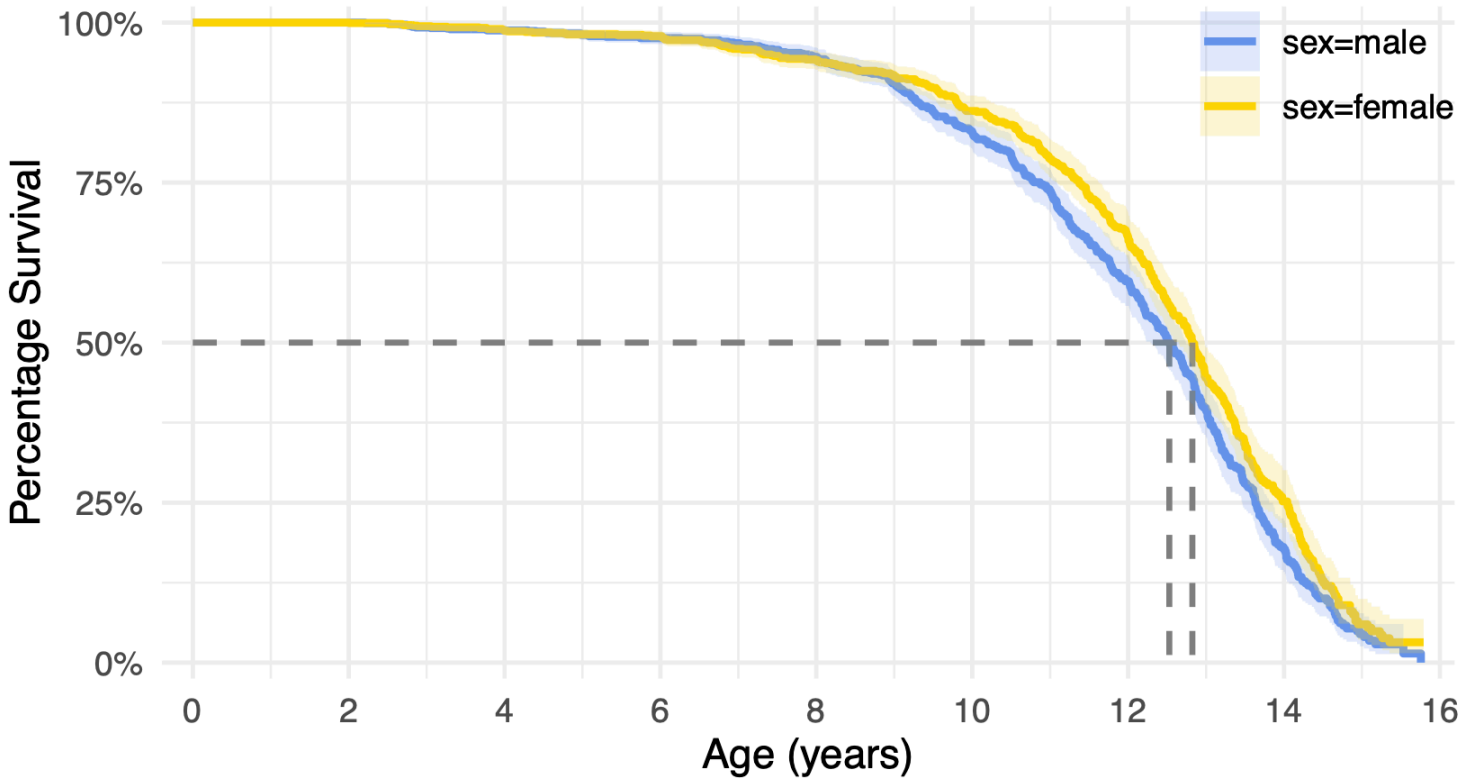


Figure 1

Survival curves for 1253 female and 1287 male Labrador Retrievers estimated with a Kaplan-Meier univariable model with sex as the covariate (male = blue, female = yellow line) with 95% confidence intervals (shaded areas). Sex-specific median survival is indicated with dashed grey lines.

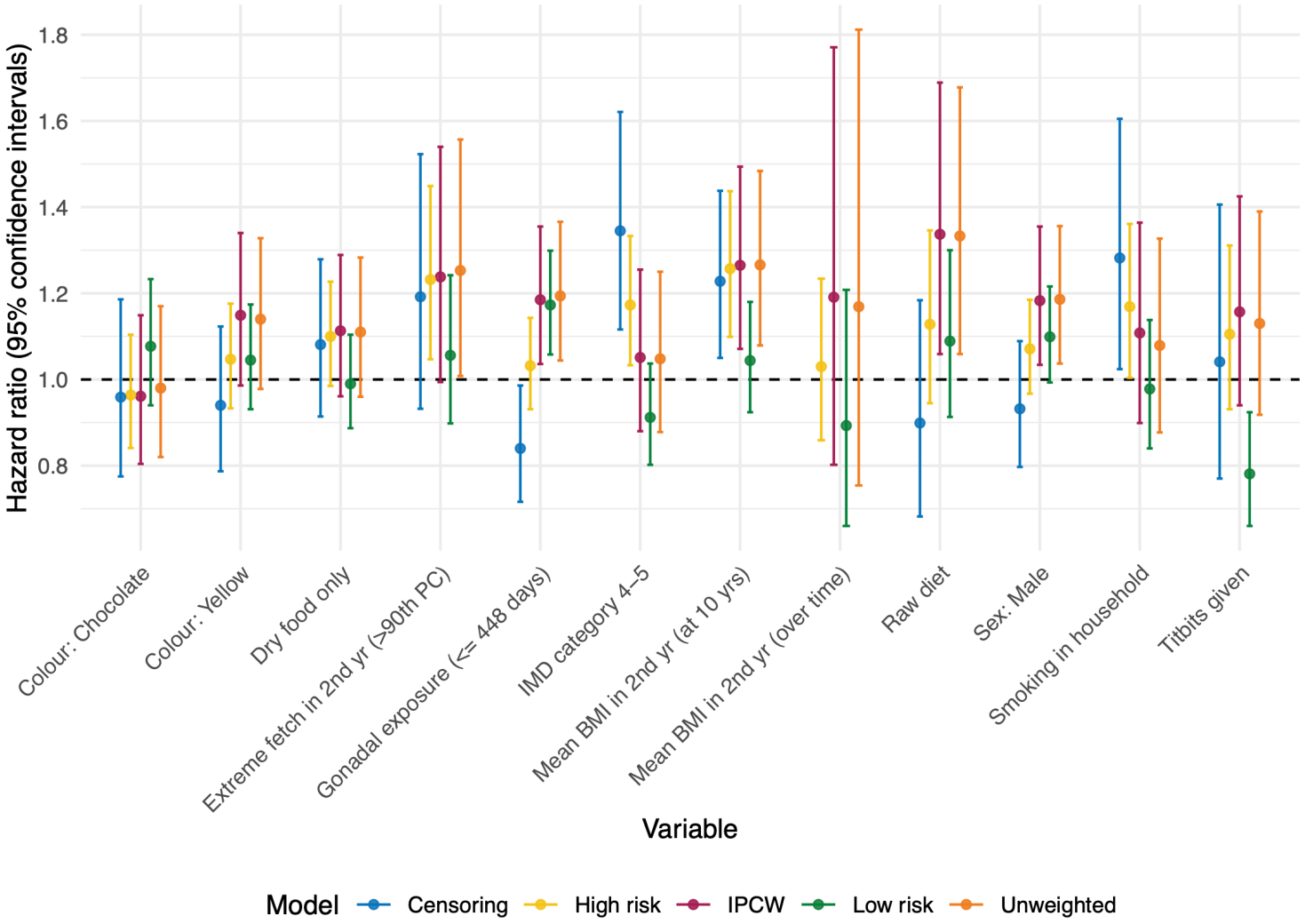


Figure 2

Hazard ratios for multiple multivariable Cox proportional hazard (Cox PH) models including 2540 Labrador Retrievers. The 'Censoring' model estimated the hazard of being lost to follow-up (LTFU, n.b. administrative censoring and deaths are classed as 'not censored'; orange) and four Cox-PH models estimated the hazard of death; the 'Unweighted' final model (blue), final model weighted by Inverse Probability of Censoring, 'IPCW' (yellow), 'High risk' (all LTFU dogs assumed to die the day after LTFU; red) and 'Low risk' (all LTFU dogs assumed to live until same age as longest-lived dog in study- 5755 days; green) models. Models share the same specifications except weighting and the censoring model does not include the time-varying effect for mean body mass index (BMI) over time. Mean BMI variables are expressed as a standardised hazard ratio interpreted as the hazard associated with a change from the 10^{th} to the 90^{th} percentile of BMI

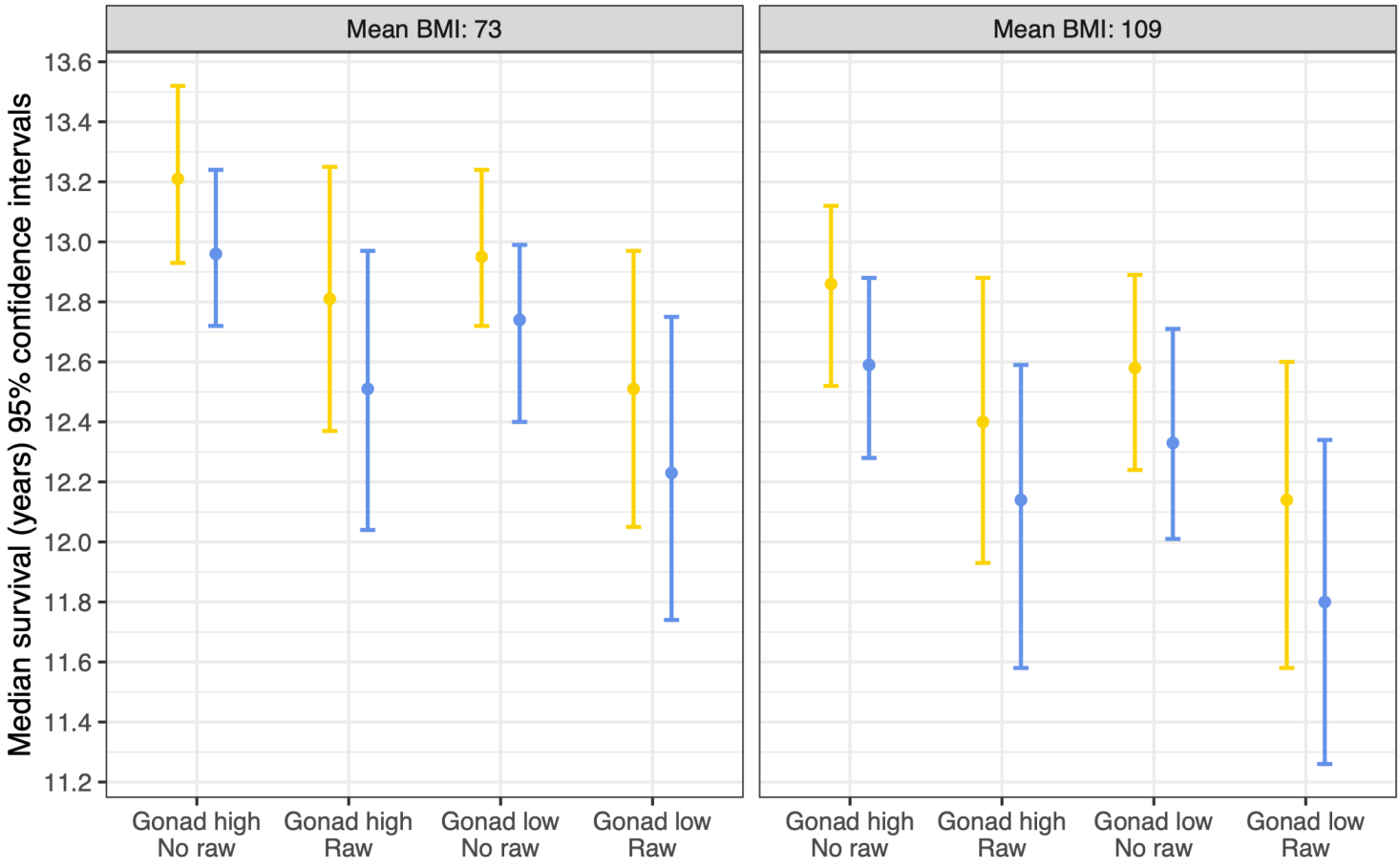


Figure 3

Effect of changing mean BMI, gonadal hormone exposure time, sex and raw diet on median survival predicted from the multivariable Inverse Probability of Censoring-Weighted (IPCW) Cox-proportional hazards model. Left plot shows estimates based on a mean BMI of 73, right plot shows mean BMI of 109 with gonadal exposure as high (>= 448 days) or low (< 448 days) and whether the dog ate a raw diet in first 2 years of life. Points and error bars are coloured by sex (male – blue, female – yellow). All dog profiles are otherwise based on an average participant; a black coated Labrador with normal FCR activity exercise levels (<90th percentile), fed a dry, non-raw diet with titbits, in a non-smoking household with a IMD between 3 and 5.

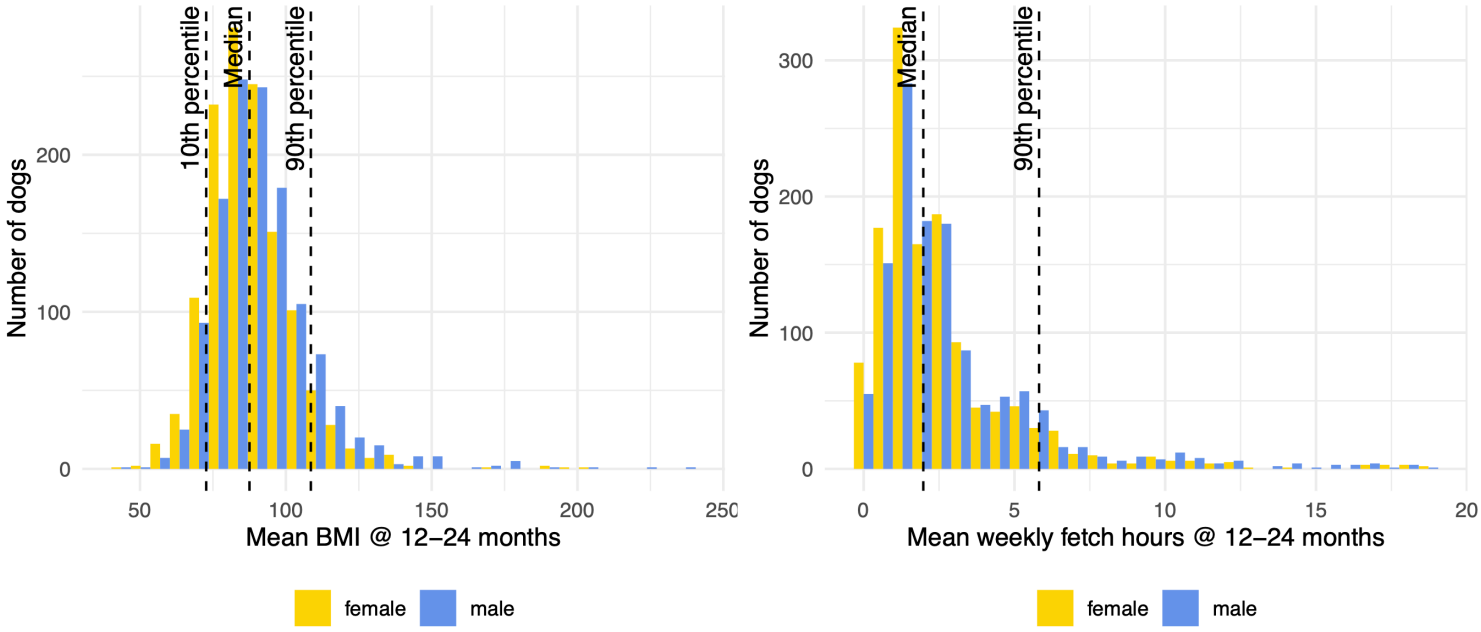


Figure 4

Histogram of mean body mass index (BMI) for dogs from 12 to 24 months of age and mean weekly hours of fetching, chasing or retrieving activity between 12-24 months of age, stratified by sex (males = blue, females = yellow) for 2540 Labrador Retrievers. Vertical black dashed lines indicate the median, 10th and 90th percentiles of the full dataset where applicable.

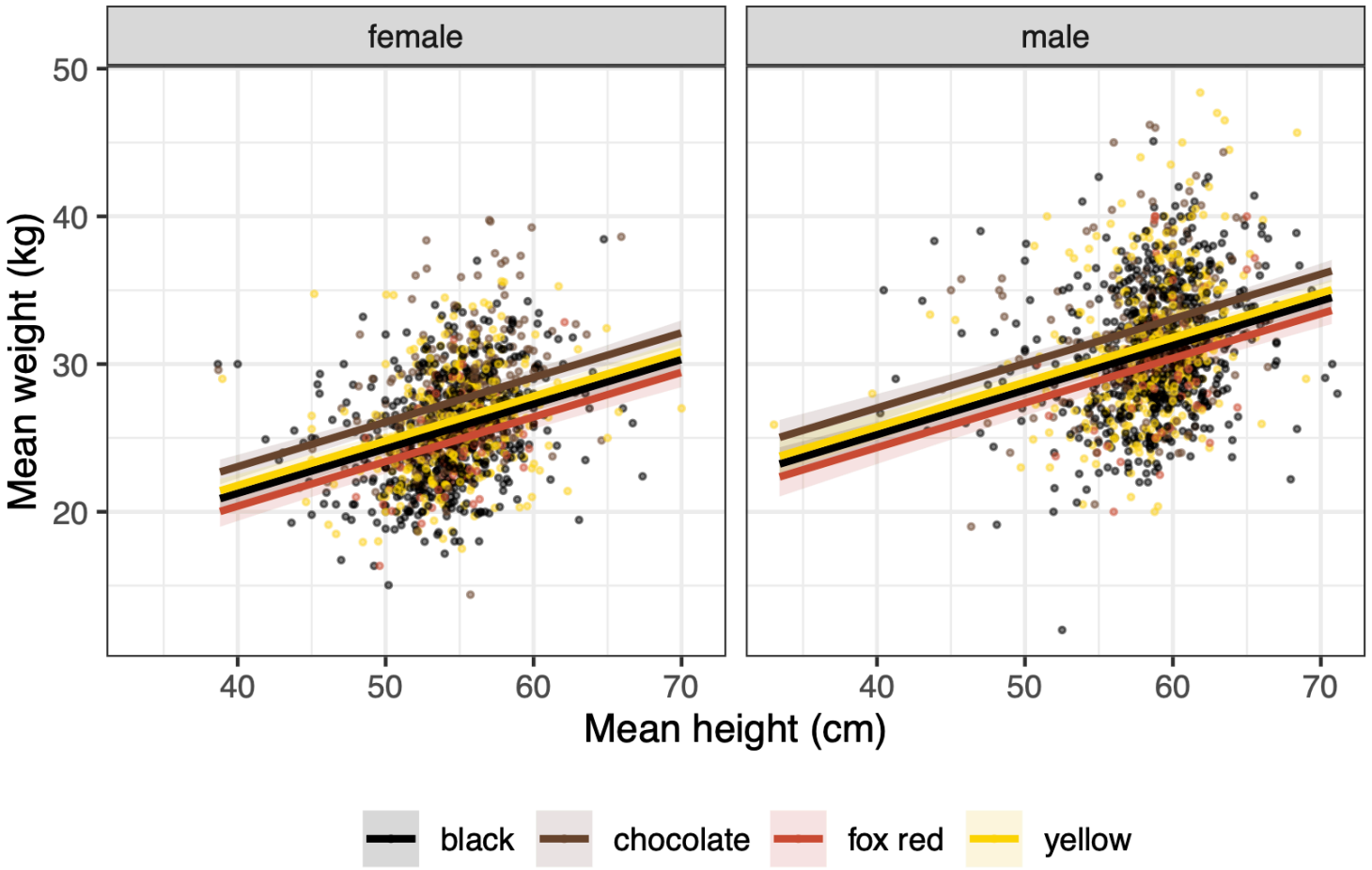


Figure 5

Mean weights and heights of 2540 Labrador Retrievers between 12 and 24 months old. Points show actual data points and lines and shaded areas show multivariate linear model predictions and 95% confidence intervals stratified by coat colour and split by sex (males left, females right). Fixed model variables for predictions were index of multiple deprivation category 1 (least deprived), mean total exercise per week (18.4 hours), no raw food and fed wet food in first two years of life.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- EarlyLifeSurvivalSupportingInformation.docx