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Growing Beagles and Foxhound-Boxer-Ingelheim Labrador Retriever mixed breeds show a forelimb-dominated gait and a cranial shift in weight support over time during a kinetic gait analysis

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OBJECTIVE
To collect kinetic gait reference data of dogs of 2 breeds in their growth period during walking and trotting gait, to describe their development, and to investigate the weight support pattern over time.

ANIMALS
8 Foxhound-Boxer-Ingelheim Labrador Retriever mixed breeds and 4 Beagles.

PROCEDURES
Ground reaction force variables (GRFs), peak vertical force and vertical impulse, and temporal variables (TVs) derived therefrom; time of occurrence; and stance times were collected. Body weight distribution (BWD) was evaluated. Six measurements, each containing 1 trial in walking and 1 trial in trotting gait, were taken at age 10, 17, 26, 34, 52, and 78 weeks. The study period started July 17, 2013 and lasted until October 7, 2015. Area under the curve with respect to increase was applied. The difference of area under the curve with respect to increase values between breeds and gaits was analyzed using either the *t* test or the Mann-Whitney test. Generalized mixed linear models were applied.

RESULTS
Significant differences in gait and breed comparisons were found. Growing dogs showed a forelimb-dominated gait. The development of GRF and TV values over the study period were described.

CLINICAL RELEVANCE
Reference values for GRFs, TVs, and BWDs in growing dogs were given. A cranial shift in weight support over time was found during trotting gait. Smaller, younger dogs walked and trotted more inconsistently.

Kinetic gait analysis is a well-established method to evaluate the gait cycle of adult healthy dogs as well as to detect and assess lameness and to evaluate treatments of various orthopedic diseases in dogs.[1–3] Ground reaction forces (GRFs), such as peak vertical force (PVF) and vertical impulse (VI), and temporal variables (TVs), such as stance time (ST) and time of occurrence (TOO), measured with a force platform gait analysis, are well described for healthy adult dogs of various breeds and mixed breeds during walking and trotting gait.[4,5]

Ground reaction forces depend on body mass, body conformation, and traveling speed.[1,6–8] Furthermore, variances in GRFs and TVs are affected by gait trial repetition and individual intraday variability.[9] Standard procedures to reduce variance are normalizing the GRFs to the body weight (BW) and using narrow speed ranges with controlled acceleration.[6] Significant correlations have been reported between GRFs and TVs with limb length. Smaller dogs take shorter, faster steps whereas larger dogs take fewer, bigger steps at the same absolute speed.[10,11] Some authors recommend normalizing speed to the distance from the ground to the margo dorsalis scapulae, hereinafter referred to as withers height (WH), to reduce variance resulting from individual body conformations.[12] Taking into account those limitations in comparability of GRFs and TVs in a heterogeneous dog group, GRFs and TVs for adult dogs are described as follows. With greater velocities, PVF increases whereas VI and ST decreases.[6] Higher ST values produce higher TOO values—meaning, time to PVF occurs later during walking than during trotting velocities.[4] The correlation of BW to GRFs and TVs is described differently. Some authors stated that without normalizing GRFs and TVs to the WH, larger, heavier dogs showed lower PVF values, higher VI values, and longer ST than smaller, lighter dogs.[1,4] Conversely, other authors described smaller GRFs and TVs for small dogs than for large dogs, except for PVF and body weight distribution (BWD).[11] They reported a negative correlation between PVF and BW in large dogs but not in small dogs. The BW or size of the dogs did not affect the BWD.

Dogs are a forelimb-dominated species and carry about 60% of their BW on the thoracic limbs and 40% on the pelvic limbs.[1,5,13] Therefore, the PVF, VI, and BWD values of the thoracic limb are higher than those of the pelvic limb. Slight differences in BWD between dogs of different breeds have been reported.[10,14,15] Studies on adult dogs of different breeds have shown that the ST is greater in the thoracic limb than in the pelvic limb, although the differences between the thoracic and the pelvic limb were not statistically significant.[4,14–18]

However, very little is known about the development of kinetic gait parameters during dogs' growth period. To the best of our knowledge, there have been only 2 studies evaluating kinetic and kinematic parameters of the gait cycle in growing dogs.[13,19] One study[13] investigated the change of the weight support pattern in Beagles from 9 to 51 postnatal weeks by determining the PVF, VI, ST, and TOO during trotting but not during walking gait. The PVF of the thoracic limb increased from 59% at postnatal week 9 to 63% at postnatal week 51, and the VI of the thoracic limb increased from 62% at postnatal week 9 to 67% at postnatal week 51, showing that the thoracic limb carried an increasing portion of the body as a dog grows. As in adult dogs, the thoracic limb carried more weight than the pelvic limb at all times. The ratio between the ST of the thoracic and the pelvic limbs increased over time with an increasing ST of the thoracic limb. The TOO did not change in the thoracic limb but increased in the pelvic limb with age, indicating that PVF occurred later during stance when the dogs grew older. The other study[19] analyzed GRFs and TVs from domestic dogs between age 4 and 15 postnatal weeks with a mean body mass increase of 2.1 to 7.3 kg, measured with force plate analysis during walking gait. The PVF of the thoracic limb was always greater than the PVF of the pelvic limb. In contrast to Helmsmüller et al,[13] the authors described an increase of PVF of the pelvic limb whereas PVF of the thoracic limb remained the same.

Basic research is important for the interpretation of kinetic parameters of growing dogs. The aim of this explorative study was to collect reference values for healthy, growing dogs during walking and trotting gait. The basic data collected aims to help evaluate data of future kinetic studies in terms of the assessment of both a normal and an abnormal gait in growing dogs. The Beagle and Foxhound-Boxer-Ingelheim Labrador Retriever (FBI) breeds were picked to collect data of a medium-size breed and a large breed, and to compare results between the 2 breeds. To be able to offer a greater variety of basic kinetic data, and to explore differences between gaits, results were collected in walking and trotting gait.

Materials and Methods

Animals

Twelve young and healthy dogs, 8 FBIs and 4 Beagles, owned by the Chair of Animal Nutrition and Dietetics, Department of Veterinary Sciences, Ludwig-Maximilians-Universität München, Germany, were recruited for the study. The study period started July 17, 2013 and lasted until October 7, 2015. Each dog was measured 6 times, starting at age 10 weeks, followed by measurements at age 17, 26, 34, 52, and 78 weeks. Time intervals were set closer during their first 6 months of living because the main growth of the dogs occurs during this period.[20] Each measurement consisted of a physical examination; measurements of WH, croup height, vertebral column length, and BW; and a gait analysis. Each gait analysis consisted of 2 trials: 1 at a walking gait and 1 at a trotting gait.

Before every gait analysis, the first author examined all dogs clinically, neurologically, and orthopedically. Dogs were excluded if they showed any signs of illness or failed to habituate to the gait analysis. At every study day, WH was measured at the margo dorsalis scapulae, croup height at the crista iliaca, and vertebra column length from the first vertebra thoracica to the apex ossis sacri; all measurements were in meters. The dog's BW in kilograms was measured with the same digital scale, operating in 100-g steps.

The study was approved by the Animal Care and Use Committee of the Centre for Clinical Veterinary Medicine, Faculty of Veterinary Medicine, Ludwig-Maximilians-Universität München, Germany (protocol no. 14-09-08-13).

Gait analysis

Force plate analysis was performed at the gait analysis laboratory of the Clinic for Small Animal Surgery and Reproduction, Ludwig-Maximilians Universität München, Germany. The dogs walked and trotted on a horizontal treadmill embedded in a platform with 2 separate belts and 4 integrated piezoelectric force plates, 2 underneath each belt. The GRF of all 4 limbs were sampled separately at 1,000 Hz. Speed was controlled by software (Simi Reality Motion Systems GmbH) in steps of 0.02 m/s. The force platform was connected to a data acquisition system and a computer with gait analysis software (Vicon MX 3+, Vicon Motion Systems Ltd.).

The first author personally guided the dogs on the treadmill for all measurements. The dogs were allowed to habituate to walking and trotting on the treadmill. Forward motion toward the guiding veterinarian was encouraged by positive reinforcement. Each gait analysis measurement consisted of 2 trials: 1 at a walking gait and 1 at a trotting gait. Each trial was limited to a maximum duration of 2 minutes. Between trials, the dogs had time to rest and recover. The dogs had access to water and food during data collection. Together with a qualified observer, each trial was evaluated to confirm foot strikes and gait. Walking and trotting gait had to be evaluated anew at every measurement because of increasing size and BW. To ensure a consistent and even movement forward, speed also had to be adapted to the 2 different breeds and depended on the individual stage of development of each dog.

In-house software (QuadruPedLocomotion, in-house software of Ludwig-Maximilians Universität München) was used to evaluate valid steps. By reviewing the vertical force curves, touchdown and liftoff events were determined manually. A valid step required each limb hitting the correct force plate without additional footfalls. The force threshold was set at the lowest possible value, depending on BW. All valid steps were selected for further analysis and exported to computer software (Microsoft Excel version 12, Microsoft Corp).

The following parameters were used in different equations to normalize GRFs to the dog's BW: PVF was expressed as percentage BW (% BW), VI was expressed as % BW per second; BW was expressed in kilograms; and gravitational acceleration (g) is expressed in 9.81 m/s^2:

$$PVF(\%BW) = GRF/(BW \times g)$$

$$VI(\%BW/s) = VI/(BW \times g)$$

ST and TOO were expressed as a percentage of the total step. To evaluate the weight support pattern, BWD was calculated for each limb with the following equation:

$$BWD\ (\%BW) = 100 \times (\text{PVF of 1 limb}/\text{Total PVF of all limbs})$$

To account for the increasing WH as well as for the increasing speed over the series of measurements, dog speed was normalized to body size with the following equation:

$$\text{Froude number} = V/(g \times WH)^{1/2}$$

where V represents absolute speed (measured in meters per second), g is gravitational acceleration (measured in 9.81 m/s^2), and WH is expressed in meters. The Froude number is a dimensionless value and allows comparing GRFs exerted by dogs running at the same Froude number based on the hypothesis of dynamic similarity[2,21]: The hypothesis predicts that animals of different sizes will use the same gait when travellig with equal Froude numbers.[22]

Data were collected separately for each limb. For each variable, the mean results for the right and left pelvic limbs and the mean results for the right and left thoracic limbs for each dog were used in the analyses.

Statistical analysis

Area under the curve (AUC) analysis is a standard method used in studies to compare data from serial measurements and to account for physiologic development over time.[23] We chose to apply AUC analysis for 2 reasons: to account for the aim of this study to record the development of kinetic parameters over time and for the correct handling of serial measurement data. AUC is defined as the sum of all the trapezoids and triangles delimited by the time-versus-variables values curve and is calculated mathematically as the integral of the curve.[23] There are 2 different ways to calculate the AUC: AUC with respect to ground (AUCg) and AUC with respect to increase (AUCi). AUCg involves the total area under the curve, whereas AUCi is calculated with reference to the first value. In contrast to AUCg, AUCi uses the first value as a reference for calculation and ignores the distance from zero, thereby emphasizing the development of variable values over time.[24] In our study, AUCi analysis was applied.

The AUCi mean values of GRF and TV variables were compared between breeds (FBI/Beagle) and between gaits (walking/trotting). The dependent-interval scaled variables PVF and VI, and the dependent-ratio scaled variables ST, TOO, and BWD, were applied to both breed and gait comparisons. The Shapiro-Wilk test was applied to all variables to check for normal distribution. Data with confirmed normal distribution were tested for significance by use of the t test and non-normal distributed data by use of the Mann-Whitney test.

Generalized mixed linear models were applied with the GRFs and TVs as dependent variables; age in weeks (tested in pairs against week 78) and breed were fixed effects, and dog identification number was a random effect. Age in weeks was tested against week 78 because at this age the dogs produced GRF and TV values similar to adult dogs. These analyses were applied separately to the GRF and TV parameters measured in walking and trotting gaits.

The GRF and TV values over time were compiled, and each marker indicates the average across subjects **(Figures 1–5)**. The figures visualized the development of GRF and TV values over time and between breeds and gaits.

The calculated Froude numbers were analyzed further either by applying the Friedman test concerning non-normal distributed data or by applying a one-way ANOVA followed by a Tukey post hoc test concerning normal distributed data. Box plots of Froude number values over time of breeds and gaits were compiled **(Supplementary Figure S1–S2)**.

All analyses were conducted using computer software (IBM SPSS statistics version 28.0, IBM; MedCalc statistical software version 18.11, MedCalc Software Ltd; RStudio version 2021.09.0+351, RStudio, PBC). Data were reported, as mean ± SD. Values of $P < 0.05$ were considered significant.

Results

Animals

Initially, 11 FBIs and 14 Beagles were identified for possible inclusion. Data of 3 FBIs and 10 Beagles could not be included in the AUCi analysis because they could not participate in all 6 scheduled trials. Dropout reasons varied from health issues to dogs who repeatedly refused to walk on the treadmill or dogs who were rehomed to private owners during the study time. To be able to include a litter of 3 FBIs, born in April 2013, their first measurement was performed at age 14 weeks. They were grouped with postnatal week 10. All following measurements of these 3 FBIs were taken at the exact age of 17, 26, 34, 52, and 78 postnatal weeks. Data for the remaining FBIs (n = 8) and Beagles (n = 4) were analyzed further. The FBI group consisted of 4 sexually intact males and 4 sexually intact females; the Beagle group contained 3 sexually intact males and 1 sexually intact female.

Mean values of kinetic parameters were compiled **(Table 1)**. Mean values of WH, BW, and speed were compiled **(Supplementary Table S1)**. Detailed results and *P* values of AUCi analyses were compiled **(Supplementary Tables S2–S5)**; only significant values of *P* are reported in the Results section. The PVF, VI, ST, TOO, and BWD values over time were compiled (Figures 1–5), and each marker indicates the average across subjects. Significant *P* values of the generalized mixed linear models are reported in the Results section.

Results of AUCi analyses of GRF and TV variables

The mean PVF of the pelvic limbs was significantly greater for the FBI group when walking compared with trotting ($P < 0.001$). The mean PVF of the pelvic limbs when walking was significantly greater for the FBI group compared with the Beagle group ($P = .028$). The mean PVF of the pelvic limbs when trotting was significantly greater for the Beagle

Table 1—Mean ± SD peak vertical force (PVF), vertical impulse, stance time, time of occurrence of the PVF, and body weight distribution determined on the basis of thoracic limb versus pelvic limb for 8 Foxhound-Boxer-Ingelheim Labrador Retriever crossbreed dogs and 4 Beagles when evaluated at walking and trotting gaits at age 10, 17, 26, 34, 52, and 78 weeks between July 17, 2013 and October 7, 2015.

			Age (weeks)					
Variable	**Group**	**Limb**	**10**	**17**	**26**	**34**	**52**	**78**
PVF walk (% BW)	Beagle	TL	62.51 ± 9.77	61.49 ± 3.90	66.74 ± 4.21	64.96 ± 5.60	67.17 ± 4.45	62.00 ± 1.94
		PL	45.13 ± 6.88	44.06 ± 10.97	44.53 ± 2.59	49.86 ± 2.37	44.21 ± 4.61	50.63 ± 3.45
	FBI	TL	59.94 ± 4.31	64.88 ± 7.20	68.46 ±7.90	65.69 ± 7.09	69.43 ± 10.6	67.01 ± 6.09
		PL	41.34 ± 1.35	42.73 ± 7.40	50.98 ± 5.47	48.33 ± 5.22	50.67 ± 3.89	49.65 ± 3.08
PVF trot (% BW)	Beagle	TL	75.54 ± 4.36	86.17 ± 9.52	93.36 ± 4.89	84.84 ± 6.86	93.42 ± 8.79	90.80 ± 4.33
		PL	55.41 ± 1.19	58.71 ± 2.62	62.30 ± 2.45	62.85 ± 3.28	62.19 ± 4.37	63.06 ± 2.11
	FBI	TL	86.39 ± 10.47	91.35 ± 9.25	97.97 ± 7.54	94.18 ± 5.40	93.51 ± 10.74	98.06 ± 4.46
		PL	65.51 ± 3.53	62.39 ± 7.53	67.70 ± 6.06	63.58 ± 3.71	63.44 ± 7.55	64.90 ± 2.67
VI walk (% BWs)	Beagle	TL	17.61 ± 1.31	18.55 ± 1.69	19.13 ± 0.95	18.06 ± 1.18	20.40 ± 2.22	17.83 ± 2.16
		PL	10.48 ± 1.23	10.97 ± 1.49	10.52 ± 1.58	11.93 ± 0.30	10.46 ± 1.49	11.54 ± 0.90
	FBI	TL	17.65 ± 2.53	16.68 ± 4.72	16.82 ± 1.91	17.22 ± 1.96	18.77 ± 1.54	18.49 ± 2.54
		PL	10.21 ± 0.74	8.77 ± 1.56	9.51 ± 1.18	8.71 ± 1.18	10.48 ± 0.76	10.63 ± 1.01
VI trot (% BWs)	Beagle	TL	12.55 ± 3.49	14.36 ± 1.14	13.66 ± 1.57	13.08 ± 1.74	14.89 ± 1.81	14.30 ± 1.46
		PL	5.80 ± 1.63	7.85 ± 0.75	6.51 ± 0.54	7.62 ± 1.72	8.27 ± 0.47	7.84 ± 1.71
	FBI	TL	17.65 ± 2.53	14.10 ± 0.86	15.00 ± 1.95	14.84 ± 1.76	16.39 ± 1.41	15.96 ± 1.28
		PL	6.93 ± 0.88	7.47 ± 1.12	7.66 ± 0.83	7.13 ± 0.91	8.22 ± 1.44	7.77 ± 0.98
ST walk (% step)	Beagle	TL	64.53 ± 2.50	66.44 ± 2.71	65.88 ± 2.64	65 06 ± 2.05	67.88 ± 4.93	64.94 ± 4.19
		PL	59.56 ± 1.55	64.13 ± 3.60	63.50 ± 3.69	64.94 ± 0.82	63.19 ± 3.59	63.63 ± 2.84
	FBI	TL	63.88 ± 5.37	60.42 ± 8.89	60.48 ± 2.64	61.30 ± 2.46	64.06 ± 3.64	64.02 ± 3.00
		PL	61.41 ± 1.94	58.73 ± 4.35	57.09 ± 3.93	56.41 ± 4.53	60.75 ± 3.73	61.55 ± 3.14
ST trot (% step)	Beagle	TL	51.17 ± 8.19	54.31 ± 2.56	50.19 ± 2.56	51.69 ± 4.34	52.94 ± 3 27	52.56 ± 4.39
		PL	39.42 ± 6.48	47.50 ± 3.19	40.88 ± 2.36	44.81 ± 5.89	48.13 ± 2.31	45.81 ± 6.07
	FBI	TL	49.57 ± 3.03	53.18 ± 4.54	52.33 ± 5.32	53.23 ± 3.56	56.00 ± 3.39	54.20 ± 3.05
		PL	41.96 ± 2.46	45.88 ± 4.95	44.03 ± 4.45	43.39 ± 3.00	47.28 ± 6.38	45.29 ± 4.04
TOO walk (% step)	Beagle	TL	16.67 ± 1.25	16.81 ± 1.57	15.79 ± 0.97	16.66 ± 1.49	17.75 ± 2.25	16.00 ± 1.92
		PL	12.65 ± 2.12	13.01 ± 1.43	12.67 ± 1.48	13.64 ± 0.83	12.76 ± 1.09	13.12 ± 1.61
	FBI	TL	19.55 ± 3.81	19.32 ± 3.25	17.82 ± 2.85	18.52 ± 2.03	22.58 ± 3.45	21.50 ± 2.25
		PL	12.65 ± 1.07	11.55 ± 1.52	12.21 ± 1.77	11.82 ± 1.60	14.65 ± 4.03	14.24 ± 2.71
TOO trot (% step)	Beagle	TL	17.90 ± 3.47	20.25 ± 0.51	20.14 ± 1.70	20.32 ± 2.22	20.77 ± 1.89	20.66 ± 2.02
		PL	18.08 ± 0.81	18.28 ± 2.61	16.57 ± 0.72	16.96 ± 1.91	18.50 ± 1.04	17.17 ± 1.95
	FBI	TL	19.59 ± 1.81	19.13 ± 1.28	21.64 ± 2.10	21.78 ± 1.74	22.97 ± 2.01	23.60 ± 1.44
		PL	16.00 ± 1.51	16.07 ± 2.56	18.50 ± 2.23	18.05 ± 1.74	18.34 ± 2.85	19.34 ± 1.80
BWD walk (% BW)	Beagle	TL	58.05 ± 1.58	58.23 ± 3.61	59.94 ± 3.01	56.50 ± 3.01	60.32 ± 2.87	55.08 ± 0.65
		PL	41.95 ± 1.58	41.77 ± 3.01	40.06 ± 2.87	43.50 ± 2.68	39.68 ± 3.97	44.92 ± 2.43
	FBI	TL	59.11 ± 2.31	60.42 ± 5.64	57.30 ±1.89	57.62 ± 2.28	57.37 ± 2.46	57.37 ± 2.92
		PL	40.89 ± 2.31	39.58 ± 5.65	42.70 ± 1.89	42.38 ± 2.28	42.63 ± 2.46	42.63 ± 2.92
BWD trot (% BW)	Beagle	TL	55.72 ± 3.61	59.32 ± 3.01	59.96 ± 0.66	57.38 ± 1.97	59.95 ± 2.96	58.99 ± 1.37
		PL	44.28 ± 3.61	40.68 ± 3.01	40.04 ± 0.65	42.62 ± 1.93	40.05 ± 2.97	41.01 ± 1.38
	FBI	TL	56.70 ± 3.09	59.47 ± 1.98	59.16 ± 1.15	59.69 ± 1.24	59.57 ± 1.25	60.16 ± 1.36
		PL	43.30 ± 3.09	40.53 ± 1.98	40.84 ± 1.15	40.31 ± 1.24	40.43 ± 1.25	39.84 ± 1.36

Results for PVF an BWD are expressed as percentage of body weight (% BW). Results for VI are expressed as percentage of body weight per second (% BWs). Results for ST and TOO are expressed as percentage of the total step (% step). BWD determined on the basis of TL versus PL.

BWD = Body weight distribution. FBI = Foxhound-Boxer-Ingelheim Labrador Retriever. PL = Pelvic limb. PVF = Peak vertical force. ST = Stance time. TL = Thoracic limb. TOO = Time of occurrence of the PVF. VI = Vertical impulse.

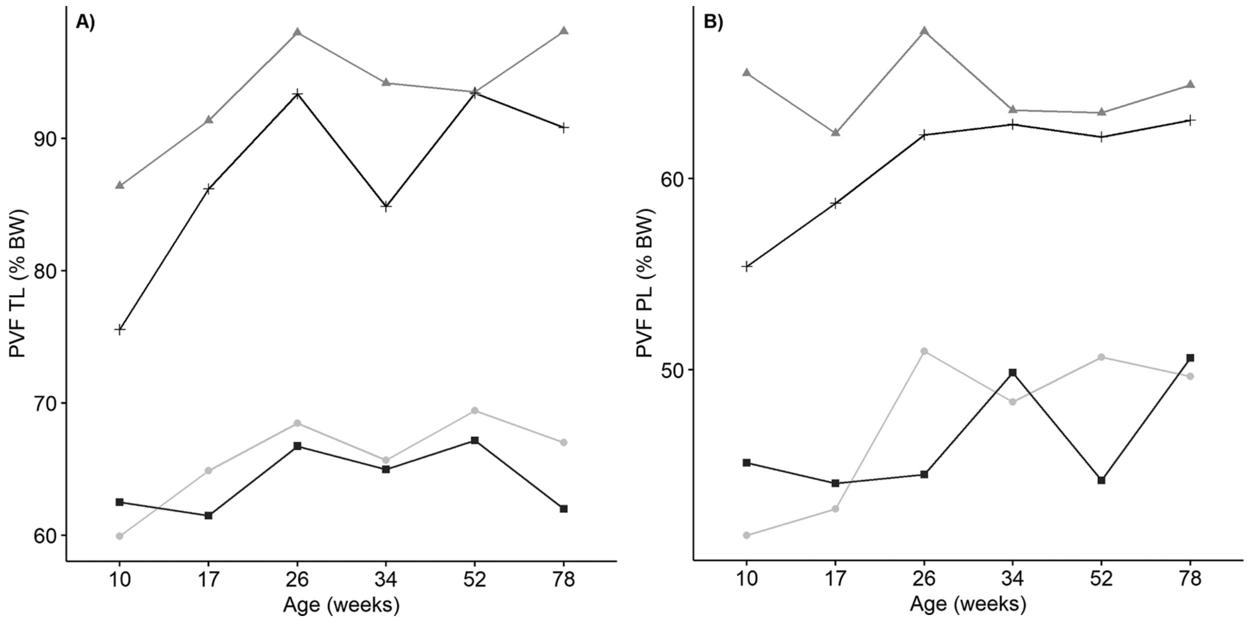

Figure 1—Mean peak vertical force (PVF) of thoracic limbs (TLs; A) and pelvic limbs (PLs; B) for 8 Foxhound-Boxer-Ingelheim Labrador Retriever (FBI) crossbreed dogs and 4 Beagles when evaluated at walking and trotting gaits at age 10, 17, 26, 34, 52, and 78 weeks between July 17, 2013 and October 7, 2015. The black lines connected by squares or plus signs represent results for the Beagle group at a walking or trotting gait, respectively. The gray lines connected by circles or triangles represent results for the FBI group at a walking or trotting gait, respectively. Results for PVF are expressed as percentage of body weight (% BW).

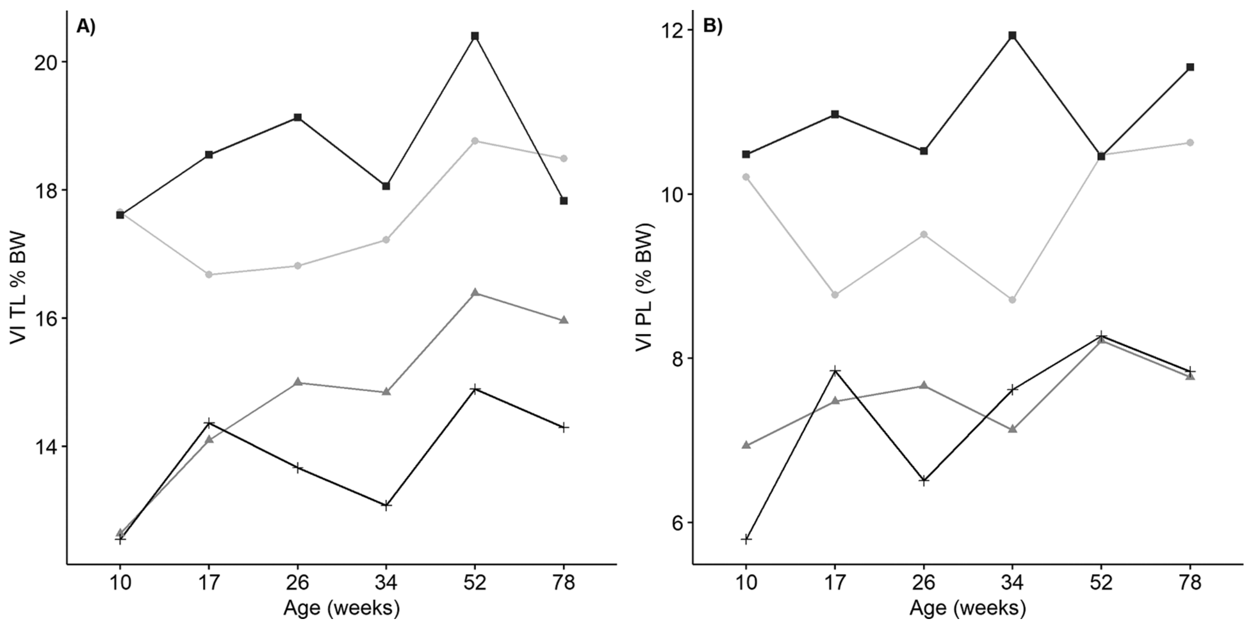

Figure 2—Mean vertical impulse (VI) of thoracic limbs (TL; A) and pelvic limbs (PL; B) for the dogs described in Figure 1 at each week evaluated. Results for VI are expressed as percentage of body weight per second (%BWs).

group compared with the FBI group (*P* = .011). There were no significant findings in all other comparisons. At all ages, in both breeds and at both velocities, the PVF of the thoracic limbs was greater than the PVF of the pelvic limbs.

The mean VI of the thoracic limbs was significantly greater for the FBI group when trotting compared with walking (*P* = .029). The mean VI of the pelvic limbs was significantly greater for the FBI group when trotting compared with walking (*P* = .018). There were no significant findings in all other comparisons. At all ages, in both breeds and both velocities, the VI of the thoracic limbs was greater than the VI of the pelvic limbs.

The mean ST of the thoracic limbs was significantly longer for the FBI group when totting

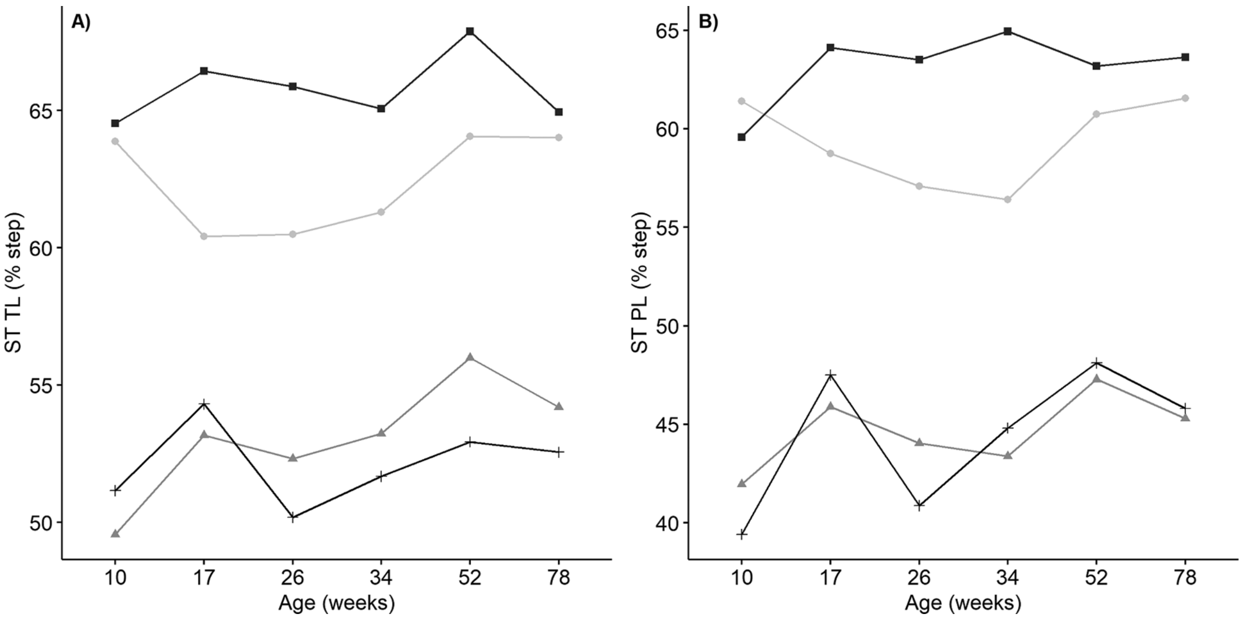

Figure 3—Mean stance times (ST) of thoracic limbs (TL; A) and pelvic limbs (PL; B) for the dogs described in Figure 1 at each week evaluated. Results for ST are expressed in percentage of the total step (% step).

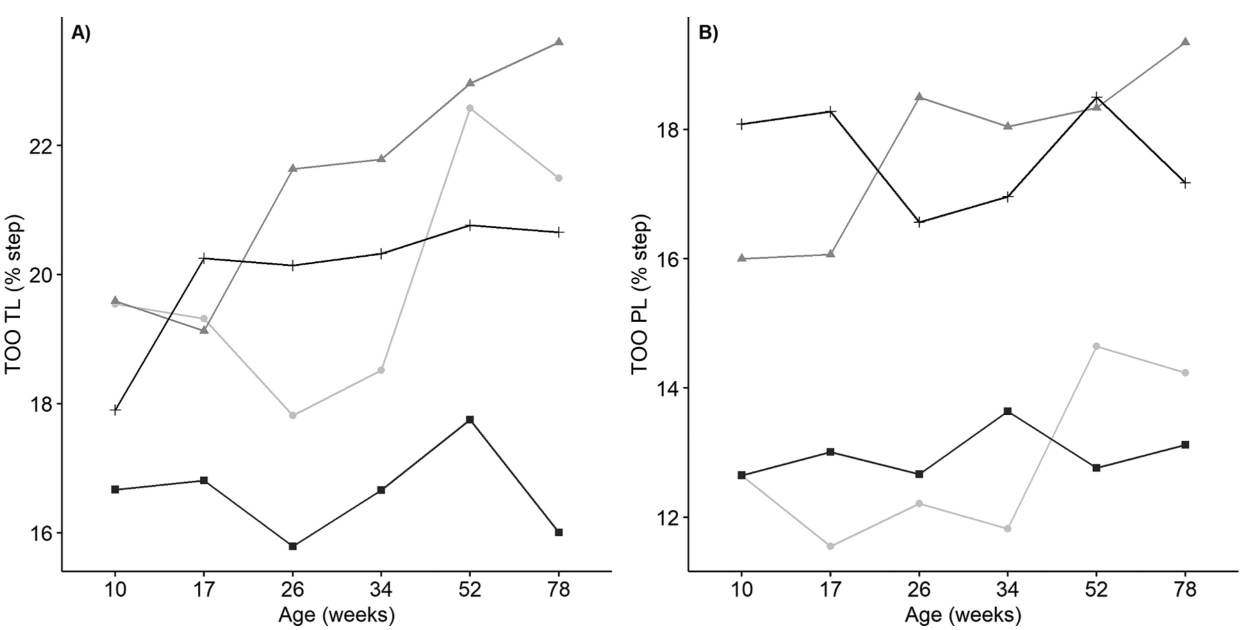

Figure 4—Mean time of occurrence (TOO) of thoracic limbs (TL; A) and pelvic limbs (PL; B) for the dogs described in Figure 1 at each week evaluated. Results for TOO are expressed in percentage of the total step (% step).

compared with walking (*P* = .021). The mean ST of the pelvic limbs was significantly longer for the FBI group when trotting compared with walking (*P* = .004). The mean ST of the pelvic limbs when walking was significantly longer for the FBI group compared with the Beagle group (*P* = .004). There were no significant findings in all other comparisons. At all ages, in both breeds and both velocities, the ST of the thoracic limbs was longer than the ST of the pelvic limbs.

The mean TOO of the pelvic limbs when walking was significantly higher for the FBI group compared with the Beagle group (*P* = .004). There were no significant findings in all other comparisons. At all ages, in both breeds and both velocities, the TOO of the thoracic limbs was higher than the TOO of the pelvic limbs.

The mean BWD of the thoracic limbs was significantly higher for the FBI group when totting compared with walking (*P* = .009). There were no significant findings in all other comparisons. At all ages,

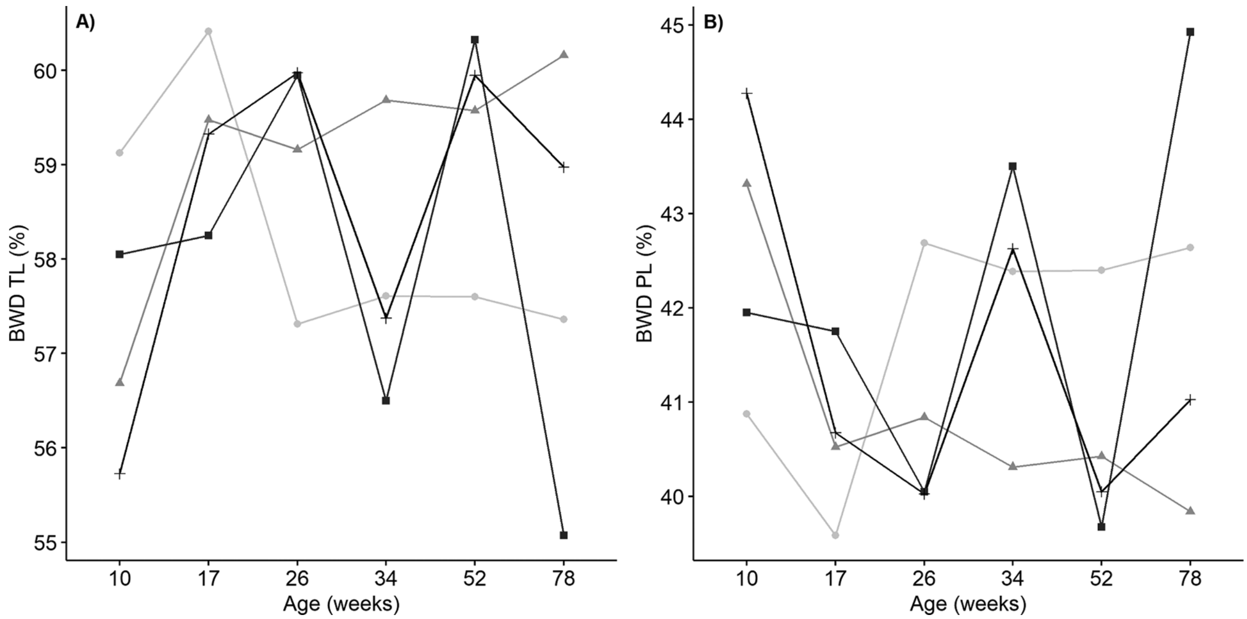

Figure 5—Mean body weight distribution (BWD) of thoracic limbs (TL; A) and pelvic limbs (PL; B) for the dogs described in Figure 1 at each week evaluated. Results for BWD are expressed in % BW.

in both breeds and both velocities, the BWD of the thoracic limbs was higher than the BWD of the pelvic limbs.

Results of generalized mixed linear model analyses for GRF and TV variables

The PVF of the thoracic limb when trotting was significantly less in postnatal week 10 compared with postnatal week 78 (*P* = .001). The PVF of the thoracic limb when trotting was significantly greater for the FBI group compared with the Beagle group (*P* = .001). The PVF of the pelvic limb when walking was significantly less in postnatal week 10 (*P* = .000) and postnatal week 17 (*P* = .006) compared with postnatal week 78. The PVF of the pelvic limb when trotting was significantly greater for the FBI group compared with the Beagle group (*P* = .010).

The VI of the thoracic limb when trotting was significantly less in postnatal week 10 (*P* = .005) and postnatal week 17 (*P* = .035) compared with postnatal week 78. The VI of the pelvic limb when walking was significantly less in postnatal week 17 compared with postnatal week 78 (*P* = .024). The VI of the pelvic limb when walking was significantly less for the FBI group compared with the Beagle group (*P* = .008). The VI of the pelvic limb when trotting was significantly less in postnatal week 10,compared with postnatal week 78 (*P* = .032).

The ST of the thoracic limb when walking was significantly shorter for the FBI group compared with the Beagle group (*P* = .001). The ST of the pelvic limb when walking was significantly shorter for the FBI group compared with the Beagle group (*P* = .022). The ST of the pelvic limb when trotting was significantly shorter in postnatal week 10 compared with postnatal week 78 (*P* = .039).

The TOO of the thoracic limb when walking was significantly less in postnatal week 26 compared with postnatal week 78 (*P* = .025). The TOO of the thoracic limb when walking was significantly greater for the FBI group compared with the Beagle group (*P* = .000). The TOO of the thoracic limb when trotting was significantly less in postnatal week 10 (*P* = .001) and postnatal week 17 (*P* = .000) compared with postnatal week 78. The TOO of the pelvic limb when trotting was significantly less in postnatal week 10 compared with postnatal week 78 (*P* = .028).

The BWD of the thoracic limb when trotting was significantly less in postnatal week 10 compared with postnatal week 78 (*P* = .007).

Results for the Froude number

A significant difference between postnatal week 10 and all other postnatal weeks was noted in the Beagles' walking gait and the Beagles' trotting gait (Supplementary Figure S1). A significant difference between postnatal week 10 and all other postnatal weeks was noted in the FBIs' walking gait. In addition, postnatal week 17 differed significantly from postnatal weeks 26, 52 and 78. A significant difference between postnatal weeks 10 and 17, respectively, to all other postnatal weeks was noted in the FBIs' trotting gait (Supplementary Figure S2).

Discussion

The main objective of our study was to collect kinetic reference data of growing dogs of the Beagle and FBI breeds during walking and trotting gaits. Our results for the Beagle group at a trotting gait were consistent with findings from a previous study.[13] Slight deviations in GRFs and TVs can be a result of physiologic and intraday variations.[25] In addition, regarding findings in trotting gait, our data showed similar results in walking gait. To our knowledge, our study was the only one to have presented GRF and TV results of the FBIs during growth periods (ie, at age 10, 17, 26, 34, 52, and 78 weeks).

The results of this study showed a significant cranial shift in weight support over time for the Beagles and the FBIs in trotting gait. Our results suggested no significant cranial shift in weight support over time in walking gait. The underlying process to a cranial shift in weight support should be taken into consideration. As in a previous study,[13] a cranial shift has been discussed for 3 possible reasons. Their observation was a more erect pelvic limb than a thoracic limb. Less protraction of the thoracic limb, together with a negative allometry of abdominal organs, leads to a cranial shift in weight support. Further insight into the underlying processes might be gained by the collection and interpretation of kinematic data of growing dogs.

We observed that our dogs walked and trotted more inconsistently at a younger age. It was more difficult to extract a valid sequence of steps during the first measurements at postnatal week 10 than during later measurements. To be able to interpret these findings in relation to clinical relevance, important factors of postnatal dog motor development need to be discussed. A previous study[26] showed that the process of maturation of the motor cortex lasts approximately 3 months. It stated that starting from the 4th postnatal week, somatotopic organization and contralateral representation of the thoracic and pelvic limbs are beginning to develop. Thereby, the repertory of movements becomes enriched, involving movements of distal joints. A previous study[13] on growing dogs reported equal conclusions about greater gait variance in younger dogs. The greater gait variance in young dogs should be taken into account when interpreting kinetic data from dogs younger than 3 months. This may be helpful for future studies with a similar aim to inform their study design and to reflect their expectations on the performance of young dogs during gait analysis.

The calculated Froude number revealed significant differences between postnatal week 10 and all following measurement points in both breeds. This indicated that the absolute speed during walking and trotting was faster when the dogs grew older. GRFs and TVs depend on the absolute speed exerted during kinetic gait analysis.[6,7] Adult dogs produce higher PVF values and lower VI, ST, and TOO values at a faster traveling speed.[4,6] This might lead to the conclusion that an increase of PVF over time might only be caused by an absolute faster traveling speed at later measurement points during our study period. However, the development of GRFs and TVs over time in our study differed from the expected influence speed has on these variables. The growing dogs in our study showed higher PVF values and higher VI, ST, and TOO values over time. These findings are consistent with findings of a previous study on growing dogs.[13] This indicated that the development of the GRF and TV values described in our study was not only affected by faster traveling speed at later measurements points during our study, but may also be part of the physiologic development of growing dogs. An ongoing development of the motor cortex and a likewise increasing ability to coordinate limb movement at a faster traveling speed might serve as explanation for the significant difference found in the Froude number. The Froude number does not account for a changing angulation of the joints or muscular usage, which might be another possible explanation for the found difference.

The results of our study concerning the PVF, VI, and BWD of the thoracic limb being higher than those of the pelvic limb in both breeds and both velocities indicated that growing dogs showed a forelimb-dominated gait from postnatal weeks 10 to 78. These findings were in accordance with findings in the literature for adult dogs.[1,5]

In addition to the collection of GRF and TV variables, our study compared data between FBI and Beagle dogs. The significant findings in breed comparison should be interpreted critically. Some authors[5] recommended normalizing all GRFs and TVs to WHs to be able to compare force plate data of different breeds. This procedure was not applied in our study, because the change in body conformation was one of the crucial factors that had to be taken into account. Regarding BWD, no differences in absolute mean values between Beagle and FBI dogs were found at postnatal week 78. Other studies stated that the Beagles' center of gravity lies farther cranially than in the Labrador Retriever; authors reported that adult Beagles carry ~60% of their BW on their thoracic limbs versus the ~58% of Labrador Retrievers.[14,15] Another previous study[27] stated that Beagles are fully grown regarding body height at about 1 year, whereas they did not reach their expected adult BW until the end of the study period at postnatal week 60. This statement corresponded well with the findings in our study and might explain the different outcome in BWD. Regarding GRFs, the PVF of the thoracic limb was greater in FBIs than in Beagles. Regarding TVs, Beagles had longer STs in comparison to FBIs. These findings corresponded well with those of a previous study[28] that compared GRFs and TVs measured on a pressure mat between adult Beagle and Retriever dogs at a walk.

Our study had several limitations. The number of included dogs was limited to puppies born at the Institute of Animal Physiology, Physiological Chemistry and Animal Nutrition during a time period of 12 months. Because of the small sample size of this explorative study, the results of the significance tests should be considered carefully. Spikes found in the Froude number in the Beagle group can possibly be explained by the small group size of 4 (Figures 1–5). The dogs did not walk and trot as consistently during their first measurements as they did when they grew older. Therefore, the selection of consecutive valid steps was more difficult during the first measurement than later on during the study.

Overall, our study was able to show a forelimb-dominated gait and a cranial shift in weight support in growing dogs during trotting gait. Found differences between the 2 investigated breeds corresponded well with findings of adult dogs and is mostly a result of different body sizes.[14,15,28] Our study gave reference values for Beagle and FBI dogs during their growth period and may be helpful in the assessment of a normal versus an abnormal gait of growing dogs. Future research containing a larger number of investigated dogs as well as dogs of other breeds is needed to collect a wider selection of reference values for growing dogs. The summary of the results of this study suggested that medium-size dogs at age 10 weeks and large dogs between postnatal weeks 10 and 17 show a greater gait variance and more inconsistency in the sequence of steps. A likely explanation might be the ongoing development of the motor cortex. This information might be helpful for agencies, handlers, and owners to reflect their expectations on the performance of young dogs and to adapt their training accordingly.

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Supplementary Materials

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