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Association of Front Limb Conformation with Lameness and Elbow Osteoarthritis in Three Chondrodysplastic Breeds: A Prospective Cross-Sectional Study

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ABSTRACT

Angular front limb deformity (ALD) describes a markedly curved forelimb shape commonly observed in certain chondrodysplastic dog breeds. Typical components of ALD include carpal valgus (VALG), external rotation of the forelimb (ROT), elbow incongruity, and lateral displacement of the radial head. These alterations may result in discomfort and gait abnormalities. However, the clinical implications and breed-related variations in forelimb structure among chondrodysplastic dogs have not been fully characterized. This prospective cross-sectional study set out to compare front limb conformation across three chondrodysplastic breeds and to determine whether these conformational traits relate to clinical signs and limb function. We also introduce new approaches for categorizing interosseous space changes and for measuring lateral radial head subluxation. In total, 224 forelimbs from 112 dogs—including 30 Standard Dachshunds, 29 Skye terriers, and 53 Glen of Imaal terriers—were assessed. VALG and ROT were evaluated using a goniometer. Elbow joint incongruity (INC) and the humeroradial angle (HRA), representing lateral radial subluxation, were measured from radiographs. Associations between limb shape, clinical signs, and functional outcomes were examined using orthopedic assessment, goniometry, radiography, and kinetic testing. Marked breed-level differences in forelimb configuration were identified. Dachshunds exhibited the least ROT and the mildest radial head subluxation. Skye terriers showed the greatest VALG, the most pronounced subluxation, and the highest proportion of moderate–severe INC. Glen of Imaal terriers demonstrated the highest ROT values. INC, ROT, VALG, and HRA occurred independently and correlated with clinically relevant abnormalities such as pain, gait alterations, reduced joint mobility, and elbow osteoarthritis. These findings indicate that VALG, ROT, and HRA could complement INC grading when selecting musculoskeletal traits for breeding programs.

Keywords: Angular deformity, Dog, Chondrodysplasia, Conformation, Range of motion, Carpal valgus, External rotation, Lameness

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Introduction

Hansen [1] originally used the term chondrodystrophy to describe dogs with shortened limbs, a phenotype now known to be associated with the fgf4 retrogene located on chromosome 18 [2]. As current genetic studies refer to this defining mutation as chondrodysplasia [2, 3], this terminology is applied throughout this manuscript when discussing short-limbed breeds. In these dogs, the substantially curved appearance of the forelimbs can also be classified as angular limb deformity (ALD) [4–7].

Within chondrodysplastic breeds, ALD arises from early closure of the distal ulnar growth plate and is considered heritable, at least in Skye terriers [4] and Basset hounds [8]. This results in a length discrepancy between the radius and ulna, the paired bones of the antebrachium. As the ulna restricts radial growth, the radius may bow in both mediolateral and craniocaudal directions [5, 9, 10], sometimes accompanied by radial torsion and/or valgus deviation of the carpus. At the proximal antebrachium, varying degrees of radial head subluxation may also appear [5, 9, 10], although no standardized method exists to quantify it. Despite their shared genetic foundation, chondrodysplastic breeds can look quite different, yet there is no published information describing how their forelimb conformations differ. It also remains unknown whether traits such as carpal valgus, limb rotation, elbow incongruity, and radial subluxation manifest concurrently or independently.

Extreme morphology may compromise performance. Pain on carpal flexion or elbow manipulation has been associated with ALD, and passive elbow extension may be reduced [4, 7, 11]. Weight-bearing dogs may position the elbow in abduction or place more load on the medial paw, and some may adopt a plantigrade stance [4, 7]. Lameness has been documented [4, 6]. Beyond lameness, the deformity may alter limb kinematics, producing a lateral swing of the elbow during walking, while most flexion–extension occurs at the shoulder [4, 7]. Kinetic methods can quantify canine locomotion [12–14], but information involving chondrodysplastic breeds or dogs with ALD remains limited [12].

Radiography and computed tomography are standard tools for assessing premature closure of the distal ulnar growth plate and associated ALD. In adult dogs, the growth plates are already mineralized, so diagnosis depends on identifying secondary deformities [4, 5, 7, 9, 11, 15]. Additional radiographic indicators include elbow incongruity and radiocarpal subluxation with remodeling of the carpal bones [4, 7, 9, 11]. Lappalainen *et al.* [6] introduced a grading system for elbow incongruity, later validated by Pulkkinen *et al.* [16], which is currently used in Finland for breed-screening programs aimed at decreasing the prevalence of elbow incongruity. Another noteworthy radiographic feature involves interosseous bone formation between the radius and ulna, described variously as interosseous synostosis, epiphyseal new bone, or calcified plaques adjacent to the distal ulna [4, 7, 9, 11]. The underlying mechanisms and clinical relevance of this finding have not been clarified.

The present study aimed to compare forelimb conformation among three chondrodysplastic breeds—Skye terriers, Glen of Imaal terriers, and Dachshunds—and to evaluate relationships between conformation, clinical signs, and limb mechanics. Additionally, we sought to establish classification methods for interosseous space findings and a quantitative measure for lateral radial head subluxation. We expected that forelimb conformation would vary across breeds and that structural differences would be linked to functional outcomes.

Materials and Methods

Approval for the project was granted by the National Animal Experiment Board in Finland (ESAVI/9184/04.10.07/2014) as well as by the University of Helsinki Viikki Campus Research Ethics Committee (Statement 2/2017). Participation required written consent from all dog owners.

Recruitment and inclusion criteria

The study employed a prospective cross-sectional design. Glen of Imaal terriers were targeted because breeders had raised concerns about their forelimb structure. Skye terriers were included due to earlier investigations conducted by our team, and Dachshunds were added as they represent the most widespread chondrodysplastic breed worldwide. Announcements were distributed via social media, and owners volunteered through their respective breed clubs on a first-registered basis. Dogs qualified if they were between 1 and 10 years of age and listed in the Finnish Kennel Club registry. Dogs with previous orthopedic operations or any illness that increased the risks associated with sedation were not eligible.

All examinations took place at the University of Helsinki Veterinary Teaching Hospital from 2015 to 2017. Prior to their appointment, owners completed a questionnaire concerning thoracic limb lameness [6].

Orthopedic examination

Following a routine physical check (HP), an ECVS-certified surgeon (SM) conducted a comprehensive orthopedic work-up. This included a visual evaluation for lameness, palpation of both thoracic and pelvic limbs, assessment of spinal comfort, and testing of conscious proprioception and the withdrawal response. Each limb and joint was reviewed for discomfort, crepitus, swelling, restricted mobility, and instability (yes/no).

Conformational and passive range of motion measurements

A veterinarian (HP) or a veterinary physiotherapist (HH) obtained all conformational measurements. Dogs were positioned squarely on a non-slip surface, while handlers maintained alignment without bearing the dog's weight or allowing leaning. A single measurement was recorded using a tape measure for: the height at the withers (using a spirit level aligned with the highest point of the scapular dorsal border), the distance from ground level to the olecranon [17], and the thoracic circumference just caudal to the scapulae. External rotation of the distal limb (ROT) and the degree of carpal valgus (VALG) were measured three times under weight-bearing with a universal goniometer following a previously described technique [18]; their mean values were analyzed. Passive joint excursions (PROM) for the shoulder, elbow, and carpus were measured three times with the dog in lateral recumbency, again using a universal goniometer as outlined earlier [19]. The averages were used for statistical purposes.

Static weight bearing and temporospatial gait analysis

Assessments related to locomotion were carried out by either a veterinarian (HP) or a physiotherapist (HH). The percentage distribution of static weight was obtained using a pressure-sensitive platform (Stance Analyzer, Petsafe, Knoxville, TN, USA) [20], calibrated before each session with an external standard weight. Dogs stood squarely with all four feet aligned on the platform's quadrants while the owner faced them [21]. At least 10 readings were collected and averaged.

Dynamic gait evaluation was completed with a pressure-sensitive walkway [22] measuring 90 cm in width and 7 m in length, operating at 240 Hz (GAITRite Electronic Walkway, CIR Systems Inc., Peekskill, NY, USA). The handler alternated sides between runs to reduce handling-induced asymmetry [23]. Data recorded at the trot included step length (cm), stance duration (s), and total pressure index. Multiple trials were conducted to ensure a minimum of 20 complete gait cycles per dog, and mean values for each metric were used. The recordings were processed with the corresponding software (GaitFour, version 40f, CIR Systems Inc., Havertown, PA, USA).

Radiographic examination and image evaluation

Dogs were sedated for imaging using intramuscular dexmedetomidine (0.1 mg/kg) combined with butorphanol (0.1 mg/kg). Radiographs were produced with a computed radiography setup equipped with an automatic exposure system, reusable plates, and a digital reader (Fujifilm FCR XG-1 CR-IR 346RU, Fuji Photo Film Co. Ltd., Tokyo, Japan). To maintain consistent quality, target S-values ranged between 100 and 300. The mediolateral (ML) antebrachial views followed the protocol described by Lappalainen *et al.* [6]. Craniocaudal (CrCd) views were taken with the beam centered at mid-radius, ensuring the entire antebrachium and the carpus were included. While the elbow was positioned either CrCd or ML, the carpal region was allowed to rest in its natural rotation. Foam pads, sandbags, and tape were used to stabilize the limb. Image review was conducted with OsiriX MD 9.0 (Pixmeo, Switzerland) or Horos DICOM viewer v.2.1.1 (Horos Project).

The ML views were examined for elbow incongruity, osteoarthritic changes, and cranial ulnar cortical remodeling (CUCR). Incongruity (INC) grades were determined as the modal value from nine separate measurements generated by three observers. These measurements originated from a repeatability study [16], although the baseline INC values were not published. INC was categorized according to an established four-level scale (INC0–INC3) (6). Osteoarthritis was identified by AL using the International Elbow Working Group criteria [24]. CUCR severity was scored by HP on a 0–2 scale **(Table 1; Figure 1)**.

Table 1. CUCR grading criteria

Grade	Description of ulnar cranial cortical new bone formation
CUCR0	All of the following criteria are met, or only minor changes are present in just one of them: - Cortical outline remains clearly defined - Cortical surface looks smooth and uniform - No bulging or periosteal new bone formation visible on the cranial ulnar cortex
CUCR1	Moderate to severe alteration in one criterion, or any degree of change in more than one of the following: - Cortical margins are ill-defined or fuzzy - Cortical surface appears irregular or heterogeneous - Periosteal new bone formation is clearly visible on the cranial ulnar cortex
CUCR2	Prominent bulging of the ulna at the level of the distal ulnar physis, with the bulge extending in a distal direction

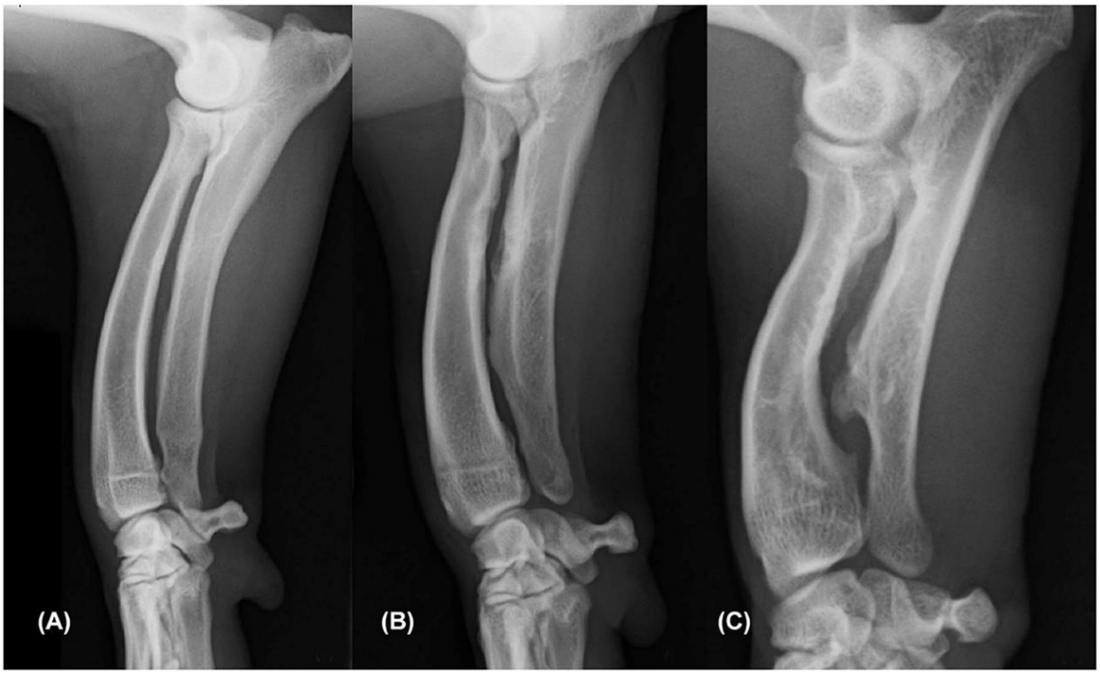
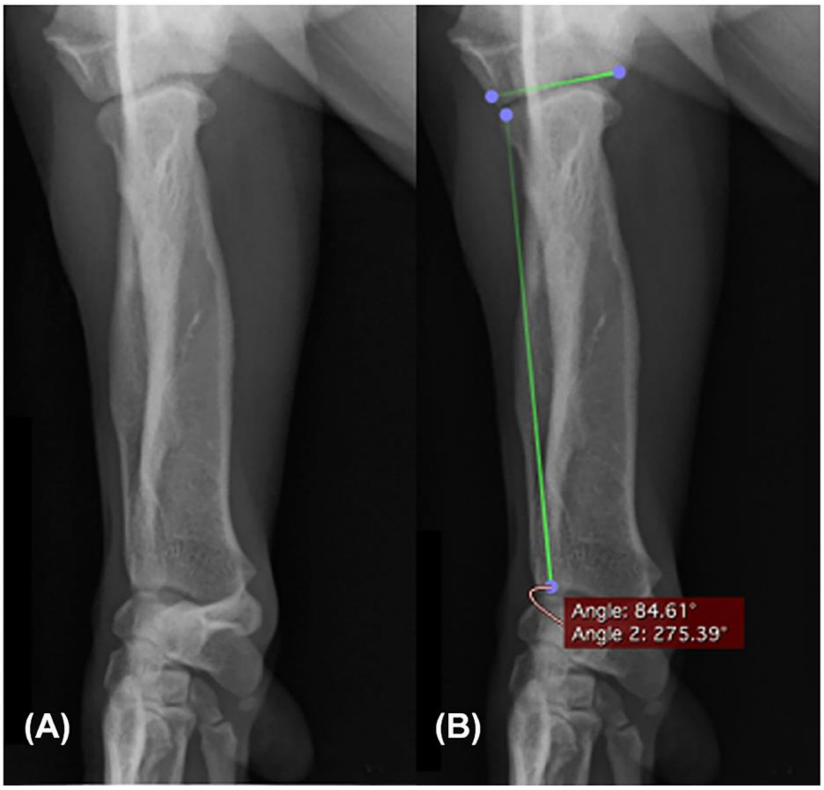


Figure 1. ML antebrachial images illustrating CUCR0 (A), CUCR1 (B), and CUCR2 (C)

For assessment of lateral radial displacement, HP measured the humeroradial angle (HRA) on the CrCd views. This single measurement was made using the software's angle tool. **Figure 2** demonstrates this method. One reference line was drawn along the humeral joint surface; the other followed the lateral border of the radius from the radial head to the lateral styloid process. The software automatically calculated the resulting angle.



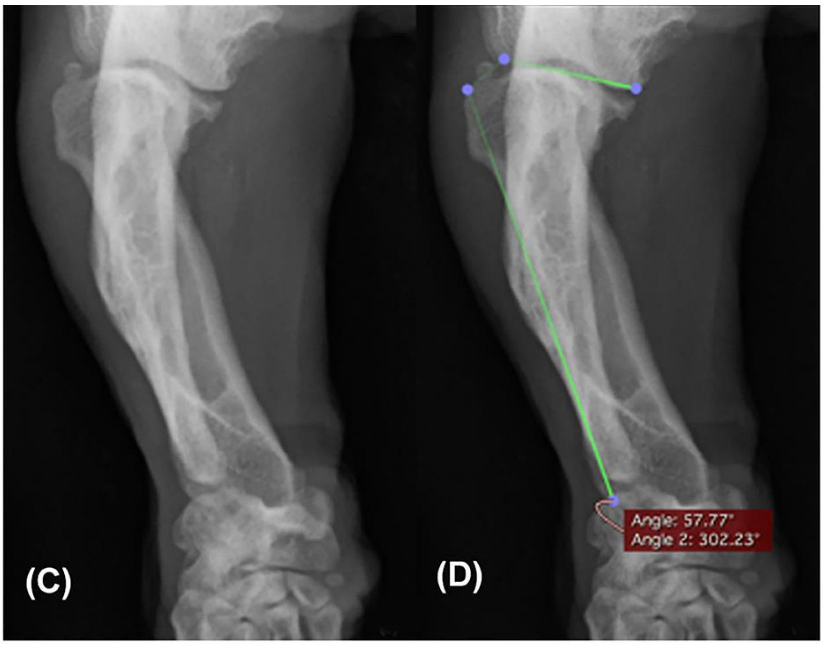


Figure 2. CrCd radiographs showing HRA measurement: an elbow with no apparent radial head displacement (A) showing 84.61° (B), and an elbow with obvious displacement (C) measuring 57.77° (D)

Statistical analysis

Front-limb conformation was represented by ROT, VALG, HRA, and INC. The influence of breed on these four measures was analyzed using linear mixed-effects models for ROT, VALG, and HRA, and mixed cumulative logit models for INC. Breed and limb were treated as fixed effects, and dog identity as the random factor. Scatter plots, fitted regression lines, and Spearman coefficients were used to explore relationships between the conformational variables.

Associations between conformation and clinical variables were analyzed with multiple model types depending on the data. Each conformation parameter was evaluated separately. Linear mixed-effects models were applied to ROT, VALG, and HRA, with the population mean of the conformation variable serving as the comparison point. For INC, mixed cumulative logit models produced odds ratios (ORs) with 95% confidence intervals (CIs). Breed and each clinical variable were entered as fixed terms, and dog identity was treated as a random effect for variables not restricted to a single limb (weight, questionnaire outcomes, orthopedic-exam lameness, height, chest circumference, static weight distribution between fore and hind limbs). Lameness was handled as a whole-animal variable due to the complex movement patterns observed and the small number of cases clearly restricted to one forelimb. Limb was added as a fixed term for limb-specific variables (pain, PROM, per-leg weight distribution, gait-analysis metrics, olecranon-to-ground distance and its ratio to chest circumference (limb/chest ratio), elbow osteoarthritis, and CUCR). Interactions between breed and each clinical variable were initially retained but removed when not statistically meaningful. However, breed-specific analyses were maintained for the relationships between INC and limb/chest ratio, and between VALG and olecranon-to-ground distance, as these varied among breeds.

A significance threshold of $P < 0.05$ was used. Analyses were performed using SAS® for Windows, version 9.4 (SAS Institute Inc., Cary, NC, USA), with all modeling done by a biostatistician.

Results

Study population

The study included 112 dogs from three chondrodysplastic breeds: 30 Standard Dachshunds (10 long-coated, 10 smooth-coated, 10 wire-coated), 29 Skye Terriers, and 53 Glen of Imaal Terriers, providing measurements from 224 forelimbs. One animal could not undergo passive range-of-motion testing due to behavior, and gait evaluation was not possible for another for the same reason. Furunculosis led to the removal of two dogs from both the static weight-bearing assessment and gait trial. Technical issues with the pressure-sensing walkway resulted in two additional dogs being omitted from gait data, and logistical problems prevented static weight-bearing measurements in two others. Radiographs were not taken for one dog because a heart murmur detected during the clinical check-up made sedation unsafe; this dog remained eligible for the other components of the project. Two dogs exhibited ALD so advanced that CrCd elbow images could not be taken. Eight radiographs were unsuitable for HRA analysis because of obliquity or overlapping thoracic soft tissues—particularly noticeable in the shortest-legged Dachshunds. The full population characteristics appear in **Table 2**. One Glen of Imaal Terrier exceeded the upper age limit by 1 year, reaching 11 years between recruitment and examination.

Table 2. Summary of population characteristics for the entire cohort and for each breed (mean ± SD, range)

Breed	N (total)	Females (F)	Males (M)	Age (years)	Weight (kg)	Height at olecranon (cm)	Height at withers (cm)	Chest circumference (cm)	Limb/chest ratio
All dogs	112	61	51	3.6 ± 2.2 (1–11)	14.5 ± 4.5 (6.0–24.8)	—	—	—	—
Dachshund	30	17	13	3.2 ± 1.3 (1–7)	9.2 ± 1.9 (6.0–12.8)	14 ± 2 (12–24)	25 ± 3 (22–36)	47 ± 4 (39–55)	0.30 ± 0.04 (0.25–0.46)
Skye Terrier	29	15	14	3.4 ± 1.9 (1–8)	14.5 ± 2.4 (10.0–21.5)	16 ± 2 (15–25)	29 ± 1 (27–32)	51 ± 8 (15–61)	0.34 ± 0.14 (0.26–1.06)
Glen of Imaal Terrier	53	29	24	4.0 ± 2.7 (1–11)	17.5 ± 3.6 (8.3–24.8)	18 ± 1 (15–22)	32 ± 3 (27–39)	58 ± 4 (46–69)	0.30 ± 0.03 (0.25–0.39)

N = number of dogs; F = female; M = male; SD = standard deviation.

Differences in front limb conformation between the breeds

Marked breed-related variation was observed in forelimb structure. Breed accounted for most of the differences across all measurement types, as shown in **Tables 3 and 4**. Every conformation variable demonstrated significant between-breed contrasts except for mean VALG, where Dachshunds and Glen of Imaal Terriers showed comparable values. No left–right discrepancies were detected within any breed. Correlation analysis revealed only minimal associations between conformation measurements, none exceeding 0.36 [25].

Table 3. ROT and VALG (goniometer) and HRA (radiographs) described as mean ± SD (range)

Breed	Front limb conformational measurements		
	ROT	VALG	HRA
Dachshund	20° ± 7° (4°–35°)	23° ± 12° (3°–57°)	78° ± 8° (58°–96°)
Skye Terrier	27° ± 10° (−7° to 43°)	33° ± 10° (11°–61°)	61° ± 10° (33°–81°)
Glen of Imaal Terrier	34° ± 14° (0°–75°)	22° ± 13° (5°–52°)	74° ± 7° (53°–90°)

ROT = external rotation of the thoracic limb; VALG = carpal valgus; HRA = humeroradial angle; SD = standard deviation.

Table 4. Counts (n) and percentages (%) for INC grades, elbow OA, and CUCR in the three breeds

Breed	Total dogs (n)	Frequencies of radiographic findings – n (%)							
		INC 0	**INC 1**	**INC 2**	**INC 3**	**OA**	**CUCR 0**	**CUCR 1**	**CUCR 2**
Dachshund	60	5 (8.3)	47 (78.3)	6 (10.0)	2 (3.3)	4 (6.7)	1 (1.7)	49 (81.7)	10 (16.7)
Skye Terrier	54	2 (3.7)	31 (57.4)	17 (31.4)	4 (7.4)	19 (35.2)	1 (1.9)	22 (40.7)	31 (57.4)
Glen of Imaal Terrier	106	29 (27.3)	72 (67.9)	5 (4.7)	0 (0.0)	0 (0.0)	20 (18.9)	81 (76.4)	5 (4.7)

N = number of dogs; INC = incongruity grade; OA = osteoarthritis; CUCR = cranial ulnar cortical remodeling.

Associations between conformation and clinical findings

When all dogs were evaluated as a combined group, significant links emerged between clinical outcomes **(Tables 2–7)** and the conformation variables ROT, VALG, HRA, and INC. These associations are listed in **Table 8**.

Table 5. Numbers (n) and proportions (%) of dogs showing pain or lameness in the orthopedic exam or reported by owners

	Orthopedic examination	**Pain**			**Questionnaire Lameness**	
Breed	**Lameness n (%)**	**Shoulder**	**Elbow**	**Carpus**	**<1 year**	**>1 year**
Dachshund	2 (3.3)	16 (26.7)	8 (13.3)	0 (0.0)	7 (11.7)	5 (8.3)
Skye terrier	4 (6.9)	6 (10.3)	15 (25.9)	8 (13.8)	15 (25.9)	7 (12.0)
Glen of Imaal terrier	16 (15.1)	5 (4.7)	10 (9.4)	12 (11.3)	14 (13.2)	13 (12.2)

Table 6. Passive joint motion (degrees) of carpus, elbow, and shoulder for the three breeds (mean ± SD, range)

Breed	**Carpus (Wrist)**		**Elbow**		**Shoulder**	
	Flexion	Extension	Flexion	Extension	Flexion	Extension
Dachshund	35° ± 5° (25°–50°)	183° ± 7° (170°–200°)	36° ± 5° (30°–45°)	142° ± 8° (125°–155°)	55° ± 5° (40°–65°)	146° ± 8° (120°–160°)
Skye Terrier	32° ± 7° (20°–55°)	186° ± 16° (155°–240°)	34° ± 4° (25°–45°)	145° ± 13° (110°–170°)	52° ± 6° (40°–65°)	153° ± 9° (130°–170°)
Glen of Imaal Terrier	36° ± 10° (20°–65°)	185° ± 12° (160°–215°)	34° ± 7° (20°–45°)	155° ± 12° (120°–170°)	51° ± 9° (25°–70°)	155° ± 10° (120°–170°)

SD = standard deviation.

Table 7. Proportion (%) of weight borne by every single forelimb and hindlimb, the front-to-hind ratio, and gait metrics (stance time in seconds, step length in centimeters, and total pressure). Values shown as mean ± SD

Breed	**Static weight bearing (%)**				**Fore/Hind ratio**	**Gait analysis**		**Total pressure index**	
	Front limbs (F)	**Total front (Ftot)**	**Hind limbs (H)**	**Total hind (Htot)**	**F/H**	**Step length (cm)**	**Stance time (s)**	**Front**	**Hind**
Dachshund	33 ± 5 (23–45)	66 ± 4 (63–69)	17 ± 3 (12–25)	34 ± 4 (31–37)	2.0 ± 0.52 (1.0–2.9)	29 ± 3	0.12 ± 0.018	22 ± 4	13 ± 2
Skye Terrier	33 ± 5 (24–42)	65 ± 7 (60–70)	17 ± 3 (12–25)	35 ± 7 (30–46)	2.0 ± 0.40 (1.1–2.8)	33 ± 3	0.15 ± 0.019	32 ± 5	19 ± 3
Glen of Imaal Terrier	33 ± 5 (22–48)	69 ± 2 (67–70)	17 ± 3 (11–23)	32 ± 2 (30–33)	2.0 ± 0.47 (1.0–3.4)	33 ± 4	0.16 ± 0.019	38 ± 8	26 ± 5

SD = standard deviation; F = load on one forelimb; Ftot = combined forelimb load; H = load on one hindlimb; Htot = combined hindlimb load; F/H = front-to-hind load ratio.

Table 8. Significant associations between conformational traits (VALG, ROT, INC, HRA) and clinical or kinematic findings

Parameter	**↑ VALG (Increased Valgus)**	**↑ INC (Increased Incurvation)**
Limb/chest ratio	↓ $p = 0.036$	↑ $p = 0.003$
Weight	↑ $p = 0.003$	–
Front limb height (Glen of Imaal Terrier)	↓ $p = 0.023$	↓ $p = 0.002$
Front limb height (general)	–	↓ $p = 0.043$
Height at withers (right)	↑ $p = 0.031$	–
Chest circumference	↑ $p = 0.027$	↓ $p < 0.001$
Limb/chest ratio (Glen of Imaal Terrier)	↓ $p < 0.001$	↓ $p = 0.011$
Shoulder pain	↑ $p = 0.027$	–
Carpal pain	↑ $p = 0.076$ (*trend)	–
Lameness >1 year (right)	↑ $p = 0.002$	–
Lameness >1 year (left)	↑ $p = 0.006$	↑ $p = 0.026$
Lameness <1 year (right)	↑ $p = 0.006$	–

Lameness (left, general)	–	↑ p = 0.038
Carpal flexion	↓ p = 0.001 / ↓ p = 0.016	–
Elbow extension	↓ p = 0.016	–
Shoulder extension	↓ p = 0.098 (∗trend)	–
Shoulder flexion	–	↓ p = 0.027
Carpal extension	↓ p < 0.001	–
Elbow joint osteoarthritis	–	↑ p < 0.001 / ↑ p = 0.001
Total pressure index – front	↑ p = 0.004	–
Total pressure index – hind	↑ p < 0.001	–
Step length – front	–	↓ p = 0.021
Step length – hind	–	↓ p = 0.005
CUCR2 vs. CUCR0	–	↑ p = 0.037
CUCR2 vs. CUCR1	–	↑ p = 0.044

↑ = increase; ↓ = decrease; VALG = carpal valgus; ROT = thoracic limb external rotation; INC = elbow incongruity; HRA = humeroradial angle; CUCR = cranial ulnar cortical remodeling.
∗ = near significance.

Increasing ROT showed clear links with several findings: dogs with higher rotation tended to weigh more, had reduced carpal flexion and extension, and more frequently demonstrated carpal discomfort. Owners also reported lameness both during development and in adulthood in dogs with greater ROT. These dogs typically had a smaller limb-to-chest ratio and stood lower at the withers. Additionally, they generated higher total pressure in both the forelimbs and hindlimbs while trotting.

Dogs exhibiting greater VALG were significantly more likely to have shoulder discomfort and owner-reported lameness during both growth and adult life. Increasing VALG was also associated with reduced carpal flexion and decreased extension of the elbow and shoulder. Similar to ROT, higher VALG was linked with a smaller limb/chest ratio.

Lower HRA, reflecting radial subluxation, was notably associated with lameness, shorter stride lengths in both the forelimbs and hindlimbs, an increased limb/chest ratio, and the presence of elbow osteoarthritis.

Higher INC grades were connected to more frequent lameness (OR 3.25, CI 1.07–9.88), reduced shoulder flexion (each 5° decrease increasing the odds of a higher INC grade by 1.35, CI 1.04–1.77), greater elbow osteoarthritis, and a smaller limb/chest ratio. CUCR1 and CUCR2 appeared more commonly alongside higher INC scores; the odds for CUCR2 vs. CUCR1 were 3.22 (CI 1.03–10.01) and for CUCR2 vs. CUCR0 were 5.77 (CI 1.12–29.80). No meaningful difference was observed between CUCR0 and CUCR1.

Breed-specific observations

Dachshunds

Among the three breeds, the Dachshund was the smallest **(Table 2)**. Only 3.3% showed lameness during the orthopedic exam **(Table 5)**, yet 26.7% displayed shoulder pain, and their shoulder extension was slightly reduced (maximum 146° ± 8°) relative to the other breeds **(Table 6)**. They also showed the lowest mean ROT (20° ± 7°). Conversely, Dachshunds had the highest average HRA (78° ± 8°), meaning elbow subluxation was less pronounced **(Table 3)**. Most Dachshunds (78.3%) were graded INC1, and elbow osteoarthritis was uncommon (6.7%) **(Table 4)**. CUCR1 was identified in most of them (81.7%) **(Table 4)**.

Skye terriers

Owners frequently observed forelimb lameness during growth in this breed (25.9%). In orthopedic examination, elbow pain was most common (31%) **(Table 5)**. Skye terriers had the highest mean VALG at 33° (±10°), with values reaching up to 61°. They also had the lowest mean HRA (61° ± 10°), with a minimum of 33°, indicating substantial lateral radial subluxation **(Table 3)**. High INC grades were most prevalent in this breed—INC2 in 31.4% and INC3 in 7.4% **(Table 4)**. CUCR2 occurred in 57.4%, the highest among the breeds **(Table 4)**. Elbow osteoarthritis was also most common in the Skye terrier at 35.2%.

Glen of Imaal terriers

Glen of Imaal terriers were the largest of the three **(Table 2)**. Lameness on orthopedic exam was documented in 15%, with carpal pain noted in 11.3% **(Table 5)**. They displayed the least carpal flexion (36° ± 10°). However, their elbow extension capacity was slightly greater (155° ± 12°) compared with the other breeds **(Table 6)**. This breed had the greatest mean front-limb ROT at 34° (±14°), reaching up to 75° **(Table 3)**. They also had the highest percentage of INC0 (27.3%), along with 4.7% graded INC2, and none graded INC3 **(Table 4)**. CUCR0 occurred most often in this breed (19%), whereas CUCR2 was the least common (5%) **(Table 4)**.

Discussion

Limb conformation

The comparison of forelimb structure across the three chondrodysplastic breeds demonstrates that the suspected early closure of the distal ulnar growth plate results in different structural and functional outcomes depending on the breed. This aligns with expectations, given that breed standards emphasize distinct forelimb characteristics. The Dachshund standard calls for “upper arms close to the ribs with free movement, elbows neither in nor out, and forearms as straight as possible, with carpi slightly nearer together than the shoulders” [26]. The Skye terrier standard describes “short, muscular limbs with forefeet pointing directly forward” [27]. Meanwhile, the Glen of Imaal terrier is expected to have “short, bowed forelimbs with feet turning slightly outward” [28]. Thus, Dachshunds favor straight forelimbs, Skye terriers short limbs with forward-facing paws, and Glen of Imaal terriers bowed limbs with mild external rotation. In our sample, some traits were more exaggerated than the standards suggest—for example, the Glen of Imaal terrier often showed far more external rotation (mean 34°, maximum 75°) than the Dachshund (mean 20°). Skye terriers also typically showed substantial proximal radial subluxation, reflected in low HRA values. Since participation relied on owner willingness, caution is warranted when generalizing these results to the entire breed population.

Clinical significance

Our results illustrate that overstated interpretations of breed standards may negatively influence dog welfare in these three breeds. Dogs with more pronounced INC tended to have shorter forelimbs, decreased shoulder flexion, higher rates of lameness during orthopedic evaluation, and a greater likelihood of developing elbow osteoarthritis. While the clinical consequences of elbow incongruity are well established, INC was not linked to pain on palpation—consistent with previous reports. Pain arising during weight bearing or movement may not be triggered during standard orthopedic examination; recumbent palpation may fail to induce discomfort even though significant lameness or limb offloading becomes apparent once the limb is used [7, 13, 29, 30].

Greater external rotation of the forelimb and increased carpal valgus were linked to reduced passive motion of the carpus and diminished extension at both the elbow and shoulder in all three breeds. From a biomechanical perspective, these findings are reasonable, even though they have not been previously described. To our knowledge, PROM values have not been documented earlier for chondrodysplastic breeds. When compared with non-chondrodysplastic dogs, the average carpal extension angle in our cohort (185°) was smaller than the value reported for Labrador retrievers (192°) [19]. Carpal flexion, however, was similar to Labradors (35° in this study vs. 32° reported) [19]. Elbow extension was notably reduced in our population (147°) compared with non-chondrodysplastic dogs (Labradors 165°) [19]. Elbow flexion, by contrast, was comparable (34–36° vs. 36°). Across all three breeds in our dataset, the mean shoulder extension (151°) was also less than previously recorded in Labradors (165°) [19]. The varying degrees of ALD observed in chondrodysplastic dogs may account for the differences between our PROM results and those seen in non-chondrodysplastic populations.

Although weight distribution did not correlate with other clinical parameters, most of the dogs bore the majority of their weight on the forelimbs (65–69%, **Table 7**). This slightly exceeds the 63% front-limb loading previously reported in chondrodystrophic dogs assessed with bathroom scales [31]. Differences in methodology and breed composition may explain the discrepancy. The weight distribution we observed aligns with that of English Bulldogs, which place 67.3% of their body weight on the forelimbs when measured with a pressure-sensitive platform [13]—the same type of system used in our study. During gait analysis, dogs with higher ROT produced significantly more total pressure in both the front and hind limbs, likely because these dogs were heavier than those with lower ROT. A lateral swing of the forelimb during the swing phase, known to occur in dogs with ALD, may also contribute [4]. For instance, if a dog with pronounced external rotation must move its limb outward to clear the ground, the body may shift additional weight to the supporting limb to maintain balance [4]. Altered limb use modifies mechanical forces acting on bones, joints, ligaments, tendons, and musculature, and even the soft tissues of the paw if paw orientation changes. Abnormal joint loading can wear articular surfaces and predispose the joint to osteoarthritis [32–34]. One limitation of our gait analysis is that trotting speed was not standardized relative to body weight. Given that some dogs with ALD had difficulty moving normally, we allowed each dog to trot at its preferred pace. To maintain internal consistency, several passes were collected to ensure at least 20 usable gait cycles per dog [35, 36].

More than 25% of Dachshunds exhibited shoulder pain during the orthopedic examination, and they also showed reduced shoulder PROM compared with the other two breeds. Shoulder dysplasia could be one possible explanation [37]. There is limited literature on the effects of chondrodysplasia on the shoulder, but this may represent another under-recognized aspect of the chondrodysplastic phenotype. The FGF4 retrogene on chromosome 18 has a mild growth-inhibiting effect on the scapula [3], which may help explain breed-specific differences in shoulder structure, similar to what is seen in distal regions of the limb.

Interestingly, the limb-to-chest ratio was associated with every conformation variable measured. Our results suggest that short limbs combined with a larger, heavier chest create a body type that is more susceptible to front-limb conformational deviations. However, dogs with smaller HRA values—indicating greater lateral elbow subluxation—had larger limb/chest ratios despite having narrower chests. In these dogs, the elevated ratio was due to very short forelimbs. A recent study on FGF4 retrogenes found that chondrodysplasia does not affect chest height or width in Alpine Dachsbracke or Schweizer Niederlaufhund [3], implying that other, yet unidentified, genes influence thoracic growth.

Novel methods for assessing radiographic forelimb conformation

Humeroradial angle

Lateral radial subluxation frequently results from premature ulnar growth plate closure in conditions such as ALD or extreme chondrodysplastic morphology, but up to now, its presence and extent have largely been judged visually [4, 5, 7, 30]. Prior reports indicate that as many as **93%** of complex biapical ALDs—common in chondrodysplastic dogs—display lateral subluxation [5, 30]. We introduced the HRA as a way to quantify this displacement within the elbow. Although the HRA resembles the CORA technique used in recent studies to assess radial curvature in ALD [38], the two methods capture different information. CORA characterizes the geometry of the radius but does not evaluate lateral radial subluxation; HRA detects subluxation but not curvature. Therefore, using both together provides a more complete anatomical assessment.

In our dataset, the HRA showed marked breed differences—the average HRA of Skye terriers was 17° lower than that of Dachshunds, indicating far more lateral subluxation. Individual variation within each breed was also substantial (33°–96°). A lower HRA (greater subluxation) was significantly correlated with shorter forelimbs, reduced stride length, pain, and elbow osteoarthritis, suggesting that decreased HRA is linked to diminished welfare in chondrodysplastic dogs. One practical limitation is that extremely short or curved forelimbs positioned close to the thoracic wall may interfere with obtaining radiographs adequate for measurement. In our study, 10 of the 224 radiographs were unsuitable for assessing HRA.

As HRA can be obtained quickly and with minimal effort from a CrCd radiograph, it has potential value as an additional view alongside the standard ML projection in screening routines. Nonetheless, accurate positioning of the typically short and curved forelimb is essential to achieve reliable measurements. The present study involved a single assessor taking one set of measurements, so intra- and inter-observer repeatability still needs to be established. Because the values appeared clinically meaningful, further validation of this method is justified. Additional research is needed to determine acceptable HRA ranges for chondrodysplastic breeds.

Cranial ulnar cortical remodeling

Cortical remodeling along the cranial aspect of the ulna is a frequent radiographic feature in chondrodysplastic dogs on ML views. We observed a specific protrusion (CUCR2) at the distal ulnar growth plate, which showed significant associations with ALD-related conformational parameters. Other cortical changes within the interosseous region (CUCR1), such as those arising from ossification of the antebrachial interosseous ligament, were not linked to the variables we analyzed. Therefore, the distinct cranial ossified bulge at the distal ulnar physis should be regarded as a separate finding, likely reflecting abnormal ulnar development **(Figure 3)**. This prominent change has received limited attention in prior literature, with only Lau [4] explicitly noting it as "distal synostosis."

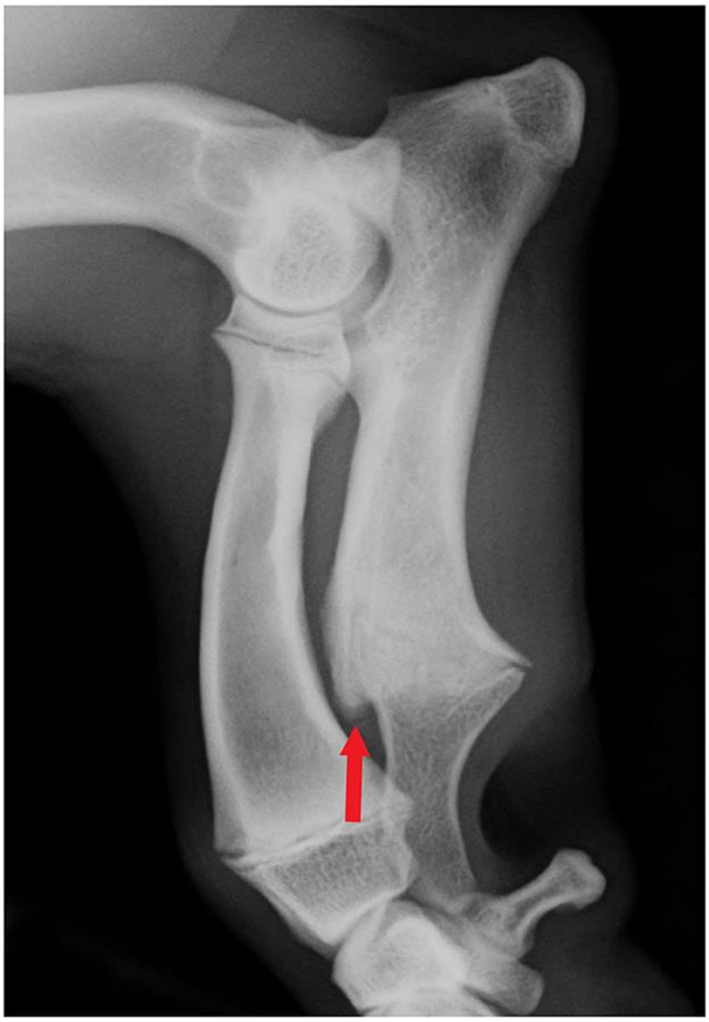


Figure 3. Mediolateral antebrachial radiograph of a young Skye terrier (not part of the study sample) with an open distal growth plate. The cortical and physeal remodeling is clearly visible (arrow)

We propose a straightforward subjective grading scheme for estimating the degree of this remodeling. Mild alterations (CUCR1) appeared frequently in Dachshunds and Glen of Imaal terriers, whereas Skye terriers displayed most of the more pronounced CUCR2 changes. This bony outgrowth likely reflects disruption of distal ulnar physeal ossification and may relate to the severity and timing of premature physeal closure. CUCR correlated with INC, as CUCR2 occurred more often in dogs with higher INC scores. It is plausible that earlier cessation of ulnar growth produces a more pronounced bulge and greater incongruity [39, 40]. Longitudinal studies of growing chondrodysplastic dogs, including reliability testing, would clarify the progression of this growth-plate disorder.

Relevance to breeding

Because premature distal ulnar physeal closure and subsequent ALD are suspected to have a hereditary basis in chondrodysplastic breeds [4], effective screening measures are warranted to minimize this debilitating condition. A noteworthy result from our study was that ROT, VALG, and HRA manifested as separate, non-dependent findings. This highlights that a single growth abnormality may lead to multiple, independent conformational deviations, meaning that no single metric is sufficient for selection decisions. For instance, although the Glen of Imaal terriers typically showed elbow congruity, many exhibited substantial carpal valgus accompanied by carpal discomfort, demonstrating the value of including external rotation measurements for this breed. Finland introduced a radiographic grading system for elbow incongruity in chondrodysplastic dogs several years ago [6, 16, 41], but integrating ROT, VALG, and HRA into the screening process could improve its effectiveness for certain breeds.

Conclusions

INC, ROT, VALG, and HRA each correspond to measurable functional alterations in the limbs and may negatively influence welfare because of associated pain and reduced mobility. These deviations, therefore, warrant careful recognition. Our data indicate that adding assessments of VALG, ROT, and HRA to routine radiographic INC grading could enhance detection of abnormal forelimb structure when selecting breeding animals. Establishing reference thresholds in future research would support this approach. Furthermore, breed standards for chondrodysplastic dogs should be reconsidered, with revisions made to remove descriptions that promote unhealthy limb conformation.

Abbreviations

CUCR, cranial ulnar cortical remodeling; HRA, humeroradial angle; INC, incongruity grade; ROT, front limb external rotation; VALG, carpal valgus.

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Ethics Statement: None

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