Evaluation of risk factors for degenerative joint disease associated with hip dysplasia in German Shepherd Dogs, Golden Retrievers, Labrador Retrievers, and Rottweilers

Gail K. Smith, VMD, PhD; Philipp D. Mayhew, BVM&S; Amy S. Kapatkin, DVM, DACVS; Pamela J. McKelvie, VMD; Frances S. Shofer, PhD; Thomas P. Gregor, BS

Objective—To determine whether age, breed, sex, weight, or distraction index (DI) was associated with the risk that dogs of 4 common breeds (German Shepherd Dog, Golden Retriever, Labrador Retriever, Rottweiler) would have radiographic evidence of degenerative joint disease (DJD) associated with hip dysplasia.

Design—Cross-sectional prevalence study.

Animals—15,742 dogs.

Procedure—Hips of dogs were evaluated radiographically by use of the ventrodorsal hip-extended view, the compression view, and the distraction view. The ventrodorsal hip-extended view was examined to determine whether dogs had DJD. For each breed, a multiple logistic regression model incorporating age, sex, weight, and DI was created. For each breed, disease-susceptibility curves were produced, using all dogs, regardless of age, and dogs grouped on the basis of age.

Results—Weight and DI were significant risk factors for DJD in all breeds. For German Shepherd Dogs, the risk of having DJD was 4.95 times the risk for dogs of the other 3 breeds combined. In all breeds, the probability of having DJD increased with age.

Conclusions and Clinical Relevance—Results indicated that the probability of having hip DJD increased with hip joint laxity as measured by use of DI. This association was breed-specific, indicating that breed-specific information on disease susceptibility should be incorporated when making breeding decisions and when deciding on possible surgical treatment of hip dysplasia. (*J Am Vet Med Assoc* 2001;219:1719–1724)

Hip dysplasia is the most common orthopedic disease of large breed dogs. The reported incidence varies greatly but may be as high as 70% in some large breeds.[1,a] The most obvious phenotypic manifestation of hip dysplasia in dogs is **degenerative joint disease (DJD)** involving the hip joints. However, conformational characteristics and environmental factors such as diet and exercise are thought to have profound effects on the phenotypic expression of DJD in individuals genotypically predisposed to hip dysplasia.[2,3] For some dogs, phenotypic expression of DJD is not radiographically evident until late in life, and for others phenotypic expression of DJD may not develop within the life span of the dog.[3] Indeed, it is the expression of DJD and its associated discomfort (in some but not all dogs) that have prompted the formation of control programs to reduce the frequency of hip dysplasia by selective breeding of disease-free dogs. Unfortunately, after 40 years of practice, such programs have had only marginal success in controlling hip dysplasia.[4-6] Attempts at reducing the frequency and severity of hip dysplasia are further complicated by empirical evidence that most dogs with hip dysplasia and DJD are without clinical signs of the disease during early life and through the reproductive years. Although epidemiologic data are not available, we estimate on the basis of clinical experience that < 5% of pet dogs with radiographic evidence of DJD (ie, phenotypic expression of hip dysplasia) will have clinically important abnormalities such as pain, lameness, and gait alterations.

This uncertainty in the expression of DJD and clinical signs of hip dysplasia has led investigators to explore other phenotypes related to hip dysplasia more closely linked to the genotype of this highly prevalent disease. Hip laxity has emerged as a candidate phenotype.

The **distraction index (DI)**, a measure of passive hip joint laxity, has been shown to be predictive of the risk of hip DJD in dogs.[7] Measurement of the DI involves measuring relative displacement of the femoral heads from the acetabula on a stress radiographic view of the pelvis; such measurements have been shown to be repeatable between and within examiners.[8]

Previous studies[7,9,10] revealed a breed-specific relationship between passive hip joint laxity, expressed as the DI, and the risk of hip DJD. These studies involved relatively small numbers of dogs representing only 2 breeds (German Shepherd Dogs and Rottweilers). We hypothesize that the relationship between passive hip joint laxity and DJD also applies to other breeds of dog, even though the specific relationship varies among breeds. We further hypothesize that the probability of dogs having DJD will be dependent on age and body weight. The purpose of the study reported here, there-

From the Department of Clinical Studies, School of Veterinary Medicine, University of Pennsylvania, Philadelphia, PA 19104.

This study was presented at the Annual Conference of the Veterinary Orthopedic Society, Lake Louise, Alberta, Canada, 2001.

The authors acknowledge the veterinarians and dog owners who contributed information to the PennHIP database.

Supported in part by Synbiotics, Inc.

Dr. Smith serves as scientific director of PennHIP and as a consultant to Synbiotics Corporation. Synbiotics Corporation is the licensee of the PennHIP technology from the University of Pennsylvania.

fore, was to determine in a large sampling of dogs whether age, breed, sex, weight, or DI was associated with the risk that dogs of 4 common breeds (German Shepherd Dog, Golden Retriever, Labrador Retriever, Rottweiler) would have radiographic evidence of DJD. A multiple logistic regression approach was used.

Materials and Methods

Information from the **University of Pennsylvania Hip Improvement Program (PennHIP)** database for 1983 through 2000 was analyzed. Dogs were included in the study if they were identified as 1 of the 4 breeds of interest, were > 4 months old at the time radiographs were taken, and did not have any history of traumatic or systemic disease. Age, sex, weight, DI, and whether dogs had radiographic evidence of DJD were recorded. For all dogs, a distraction radiographic view of the pelvis and a compression radiographic view of the pelvis had been submitted to PennHIP for evaluation, along with the ventrodorsal hip-extended radiographic view. Periarticular osteophytosis, subchondral bone sclerosis, and joint remodeling evident on a ventrodorsal projection of the pelvis obtained with the hip joints extended were considered evidence of DJD. Subluxation of the hip joints on the ventrodorsal hip-extended radiographic view was not considered evidence of DJD. The DI had been measured as described.[11]

Statistical analyses—For each breed, a multiple logistic regression model incorporating age, sex, weight, and DI as potential risk factors for DJD was constructed. Disease-susceptibility curves were derived for each breed, using all dogs regardless of age. Dogs of each breed were then grouped according to age at the time radiographs were obtained (4 to 11 months old, 12 to 23 months old, ≥ 24 months old), and additional disease-susceptibility curves were derived for each age group for each breed. **Receiver operating characteristic (ROC)** curves were then created to identify the DI associated with maximal sensitivity for predicting which dogs had radiographic evidence of DJD. All analyses were performed with standard software.[b] Values of $P < 0.05$ were considered significant.

Results

A total of 15,742 dogs, comprising 3,729 German Shepherd Dogs, 4,545 Golden Retrievers, 6,277 Labrador Retrievers, and 1,191 Rottweilers met the inclusion criteria (**Table 1**). Of these, 8,715 (55.4%) were female, and 7,027 (44.6%) were male.

Logistic regression indicated that DI, weight, and breed were significant risk factors for radiographic evidence of DJD. Of the factors tested, DI was the best predictor of DJD. Sex was not included in the final models, because it was not a significant risk factor for DJD. Distraction index was a significant risk factor for DJD in all breeds and in all age groups of all breeds (**Table 2**). In dogs ≥ 24 months old, each 0.1 increase in DI was associated with a corresponding increase in the probability of having DJD of 2.4, 2.3, 2.7, and 1.9 times for German Shepherd Dogs, Golden Retrievers, Labrador Retrievers, and Rottweilers, respectively. In dogs between 12 and 23 months old, each 0.1 increase in DI was associated with a corresponding increase in the probability of having DJD of 2.6, 2.5, 2.4, and 1.9 times for German

Table 1—Signalment of 15,742 dogs used in a study to determine whether age, breed, sex, weight, or distraction index (DI) was associated with the risk that dogs of 4 common breeds would have radiographic evidence of degenerative joint disease (DJD)

Variable	German Shepherd Dog	Golden Retriever	Labrador Retriever	Rottweiler
No. of dogs	3,729	4,545	6,277	1,191
Age (mo)*	16.7 ± 12.76	19.0 ± 14.05	18.3 ± 13.79	19.0 ± 14.79
Weight (kg)*	28.5 ± 6.61	27.9 ± 5.93	28.7 ± 6.35	36.7 ± 10.18
DI*	0.43 ± 0.15	0.56 ± 0.15	0.51 ± 0.16	0.55 ± 0.16
No. (%) with DJD	376 (10.1)	381 (8.4)	378 (6.0)	144 (12.1)

*Data are given as mean ± SD.

Table 2—Results of logistic regression analysis of the association between radiographic evidence of DJD and age, weight, and DI for 4 common breeds of dogs

			DI			Weight	
Breed and age (n)	Mean age (mo)	No. with DJD (%)	Mean	RR*	*P* value	RR†	*P* value
German Shepherd Dogs							
4 to 11 months (1,238)	6.7	67 (5.4)	0.5	2.6	< 0.001	1.007	0.546
12 to 23 months (1,814)	15.7	148 (8.2)	0.39	2.6	< 0.001	1.734	< 0.001
≥ 24 months (677)	38.1	161 (23.8)	0.41	2.4	< 0.001	1.248	0.004
Golden Retrievers							
4 to 11 months (1,442)	7.0	55 (3.8)	0.63	2.4	< 0.001	1.382	0.021
12 to 23 months (1,854)	16.5	115 (6.2)	0.53	2.5	< 0.001	1.029	0.006
≥ 24 months (1,249)	36.7	211 (16.9)	0.53	2.3	< 0.001	1.033	< 0.001
Labrador Retrievers							
4 to 11 months (2,151)	7.0	65 (3.0)	0.6	3.1	< 0.001	1.045	< 0.001
12 to 23 months (2,668)	16.8	149 (5.6)	0.47	2.4	< 0.001	1.028	< 0.001
≥ 24 months (1,460)	37.7	164 (11.2)	0.48	2.7	< 0.001	1.025	< 0.001
Rottweilers							
4 to 11 months (502)	6.8	28 (5.6)	0.6	3.1	< 0.001	1.004	0.791
12 to 23 months (251)	16.4	26 (10.4)	0.55	1.9	< 0.001	1.002	0.890
≥ 24 months (438)	34.6	90 (20.5)	0.5	1.9	< 0.001	1.019	0.011

RR = Risk ratio.
*For each 0.1 increase in DI. †For each 1.0-lb increase in body weight (to convert to RR for each 1.0-kg increase in body weight, multiply RR by 2.2).

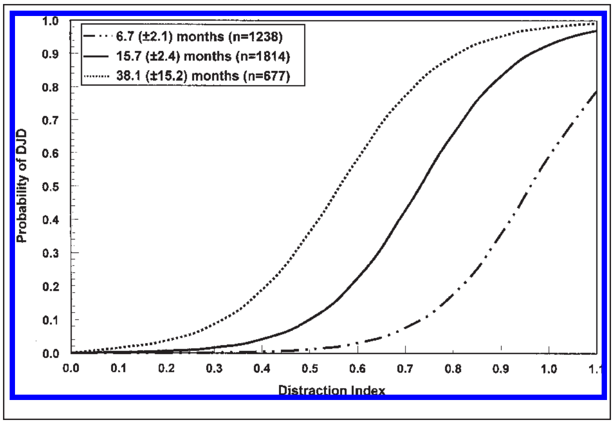

Figure 1—Probability of radiographic evidence of degenerative joint disease (DJD) as a function of distraction index (DI) in German Shepherd Dogs grouped on the basis of age (mean ± SD). The curve for dogs older than 24 months is shifted to the left because of increased expression of DJD in older dogs.

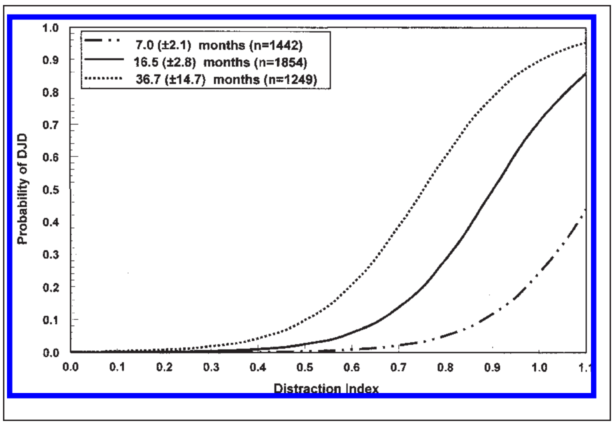

Figure 2—Probability of radiographic evidence of DJD as a function of DI in Golden Retrievers grouped on the basis of age (mean ± SD). Golden Retrievers ≥ 24 months old were 2.3 times as likely to have DJD for every 0.1 increase in DI.

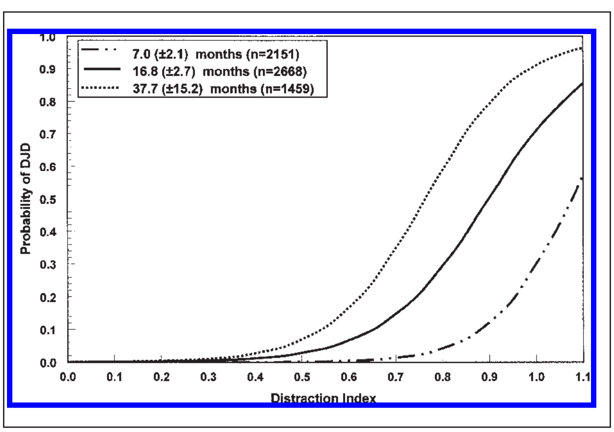

Figure 3—Probability of radiographic evidence of DJD as a function of DI in Labrador Retrievers grouped on the basis of age (mean ± SD). Labrador Retrievers ≥ 24 months old were 2.7 times as likely to have DJD for every 0.1 increase in DI.

Shepherd Dogs, Golden Retrievers, Labrador Retrievers, and Rottweilers, respectively. In dogs between 4 and 11 months old, each 0.1 increase in DI

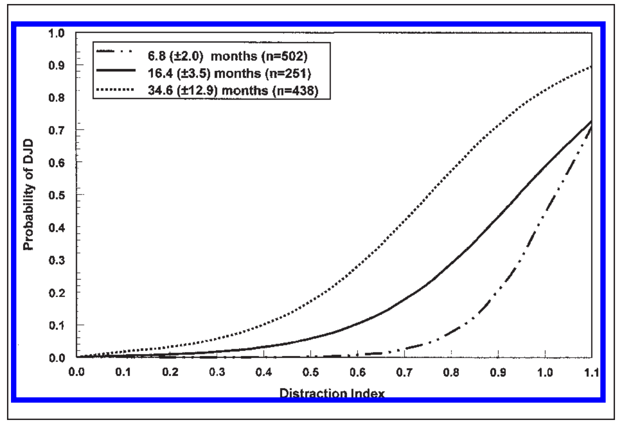

Figure 4—Probability of radiographic evidence of DJD as a function of DI in Rottweilers grouped on the basis of age (mean ± SD).

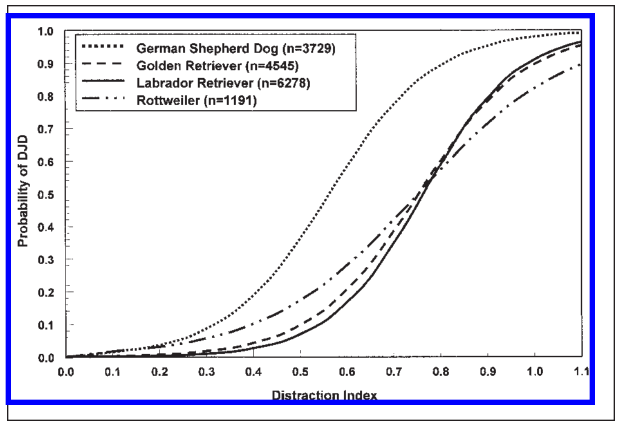

Figure 5—Probability of radiographic evidence of DJD as a function of DI for dogs of 4 common breeds that were ≥ 24 months old. Notice the spatial shift to the left for the German Shepherd Dog breed, indicating an increased probability of DJD for any given DI, compared with the other breeds.

was associated with a corresponding increase in the probability of having DJD of 2.6, 2.4, 3.1, and 3.1 times for German Shepherd Dogs, Golden Retrievers, Labrador Retrievers, and Rottweilers, respectively. For all breeds, the disease susceptibility curves shifted to the left with age of dog at time of evaluation (**Fig 1–4**).

Weight was a significant risk factor in all breeds for dogs ≥ 24 months old (Table 2). However, weight was not a significant risk factor in Rottweilers < 24 months old or in German Shepherd Dogs < 11 months old.

The risk of having DJD was significantly different among breeds. For German Shepherd Dogs, the probability of having DJD was 4.95 times the probability for dogs of the other 3 breeds combined.

The disease-susceptibility curve for German Shepherd Dogs ≥ 24 months old was shifted to the left, relative to curves for dogs of the other breeds that were ≥ 24 months old (**Fig 5**); however, the shape of the curve for German Shepherd Dogs was similar to the shape of the curve for Golden Retrievers and Labrador Retrievers. Rottweilers had a flatter curve than the other 3 breeds.

Examination of the ROC curves (not shown) indicated that DI associated with a sensitivity of 100% (negative predictive value = 1) for detecting DJD in German Shepherd Dogs, Golden Retrievers, Labrador Retrievers, and Rottweilers were 0.28, 0.32, 0.38, and 0.35, respectively.

Discussion

Results of previous studies[7,9] indicate that passive hip joint laxity is the primary risk factor for development of DJD in dogs with hip dysplasia. It has been hypothesized that in some dogs, passive joint laxity is transformed into functional laxity during weight bearing, thereby exposing the cartilaginous surfaces of the joint to excessive stresses. These stresses cause cartilage damage and microfracture, release of inflammatory mediators, and, ultimately, the changes associated with DJD.[7] Functional laxity appears to be both necessary and sufficient for development of DJD; however, no method for accurately quantifying functional hip joint laxity in dogs is presently available. Conversely, passive hip joint laxity alone appears to be necessary, but not sufficient, for development of DJD. That is, dogs with minimal passive hip joint laxity (eg, DI < 0.3) rarely develop DJD, but dogs with greater amounts of passive laxity (eg, DI > 0.3) may or may not. Results of a previous study[10] involving a small number of dogs suggested that for any given degree of passive hip joint laxity (DI > 0.3), Rottweilers were less likely to have hip DJD than were German Shepherd Dogs.

In the present study, DJD-susceptibility curves indicated that for German Shepherd Dogs, Labrador Retrievers, Golden Retrievers, and Rottweilers there was a sigmoidal relationship between DI and probability of DJD. Thus, dogs with low DI had a low probability of having DJD, and dogs with high DI were very likely to have DJD. It is important to note that even for extremely tight hips (DI < 0.3), the logistic regression model indicated a small but finite probability that dogs may develop DJD, and conversely, not all dogs with the loosest hips (DI > 0.7) developed DJD within the age interval of this study. On the other hand, ROC curves indicated that DI thresholds associated with 100% sensitivity (negative predictive value = 0) did indeed exist and were 0.28, 0.32, 0.38, and 0.35 for German Shepherd Dogs, Golden Retrievers, Labrador Retrievers, and Rottweilers, respectively.

The slope of the disease-susceptibility curve is a reflection of how rapidly the risk of DJD increases relative to an increase in DI; this can also be expressed as a risk ratio (Table 1). The steep middle section of the disease-susceptibility curves indicated that for the dogs with DI in this range, the risk of having DJD varied widely, especially when confidence limits were taken into account. However, on average, the higher the DI, the greater the probability that dogs would have DJD.

A comparison of the DJD-susceptibility curves for dogs of all 4 breeds that were ≥ 24 months old revealed a spatial shift to the left for the German Shepherd Dog breed, although all curves had the same general sigmoidal shape. Rottweilers had a flatter disease-susceptibility curve, reflecting a relatively lower risk ratio of a 1.9-fold increase in the probability of DJD for each 0.1 increase in DI, compared with risk ratios of 2.4, 2.3, and 2.7 for German Shepherds Dogs, Golden Retrievers, and Labrador Retrievers, respectively. This less sigmoidal and more linear curve may mean that establishing a threshold DI below which dogs would be expected to rarely develop DJD may be less applicable for this breed than for other breeds. Conversely, it may represent a limitation of the logistic regression model, because an analysis of the data by ROC curves did identify a DJD threshold for all of the breeds; for Rottweilers, the threshold below which no DJD was observed was 0.35.

For all 4 breeds in the present study, the prevalence of DJD increased as age increased, resulting in a spatial left shift and a more sigmoidal shape to the DJD-susceptibility curves for the older age groups (Fig 1–4). Thus, for a given DI, the probability that a dog would have DJD varied substantially with age group. These results must be viewed cautiously, however, because in many dogs with hip dysplasia, DJD is not radiographically evident until after the first year of life. As an example, results of the present study indicated that Rottweilers between 4 and 11 months old that had a DI of 0.8 had less than a 10% chance of having DJD, whereas Rottweilers between 12 and 23 months old with the same DI had approximately a 30% chance of having DJD, and Rottweilers ≥ 24 months old had approximately a 58% chance of having DJD. Thus, these graphs illustrate the importance of examining radiographs obtained after 24 months of age for evidence of DJD. Data on lifelong hip status would be required to appreciate a truer relationship between passive hip joint laxity and hip DJD.

In previous longitudinal studies[2,3,12] of Labrador Retrievers genetically predisposed to develop hip dysplasia, some dogs did not have radiographic evidence of DJD until they were > 2 years old, and others did not have it until they were > 5 years old. Prevalences of DJD were 42, 52, and 68% at 2, 5, and 8 years of age, respectively. Thus, we believe that disease-susceptibility curves in the present study would have had an even more extreme sigmoidal shape if mean age of dogs ≥ 24 months old had been greater, because more dogs would have had a chance to develop DJD. We further speculate that this trend would be more apparent with increasing age but would eventually reach a limit with the midportion of the curve nearly vertical between a DI of 0.3 and a DI of 0.4, depending on the breed.

The criteria used to diagnose DJD radiographically can vary among examiners, along with the grades assigned by individual examiners in regard to severity of DJD.[8,13] Criteria used for the radiographic diagnosis of DJD in the present study were similar to those used by the Orthopedic Foundation for Animals. If more inclusive criteria (eg, including Morgan lines as evidence of DJD[14]) had been used to diagnose DJD, it is likely that graphs in the present study would have been shifted to the left, reflecting an increased risk of having DJD for any given DI.

Results of the present study are of great clinical importance, particularly for veterinarians providing advice to breeders of purebred dogs. When choosing breeding stock, breeders need the best possible information regarding which dogs to mate to exert maximal selection pressure against hip dysplasia. The breed-specific nature of the disease-susceptibility curves in the present study indicates that breed-specific breeding advice is required. For example, the probability of a dog having DJD was significantly higher for German Shepherd Dogs in the present study than for dogs of the other 3 breeds. This was represented by a left shift of the disease-susceptibility curve for German Shepherd Dogs, compared with curves for the other breeds. Thus, German Shepherd Dogs in the present study appeared to be less tolerant of passive hip joint laxity than were dogs of the other breeds, in that for any given DI, the probability that a German Shepherd Dog would have DJD was higher than the probability that a dog of any of the other breeds would (Fig 1), despite tighter hip joints (lower DI scores) in the German Shepherd Dogs (mean DI, 0.41 for German Shepherd Dogs, 0.53 for Golden Retrievers, 0.48 for Labrador Retrievers, and 0.5 for Rottweilers). It has been hypothesized that this laxity intolerance could be attributable to conformational characteristics of the breed.[7] German Shepherd Dogs have less muscle mass stabilizing the hip joint than do Rottweilers,[15] and greater pelvic muscle mass has been associated with a lower incidence of hip dysplasia within and between breeds.[15] Large active muscle mass may inhibit the transformation of passive laxity into functional laxity as the dog ambulates and, thus, decrease the stresses on articular cartilage that lead to degenerative changes. Alternatively, a breed-specific defect in joint sense or proprioception could allow the hip to subluxate aberrantly during weightbearing. The German Shepherd Dogs' posture may also play a role. Ambulation with flexed hip, knee, and tarsal joints produces high joint-reaction forces to balance the moments generated about the hip joints. Such increased forces may favor the conversion of passive to functional hip joint laxity.

Environmental factors, including diet, have been shown to have significant effects on the incidence and severity of DJD in dogs with hip dysplasia. In previous studies,[2,3] sex-matched Labrador Retriever litter mates were paired, and 1 member of each pair was fed ad libitum, whereas the other member was fed 25% less than the amount consumed by the dog that was fed ad libitum. Dogs fed ad libitum weighed more and had 4 times the incidence of DJD at 5 years of age than did the limit-fed dogs and almost 5 times the incidence of DJD at 8 years of age. The role of exercise, another environmental factor, in the development of DJD in dogs with hip dysplasia is difficult to quantify because of the complexities involved in developing suitable longitudinal studies. However, we hypothesize that, given the same level of functional laxity, dogs that are heavily exercised will impose higher stresses on articular cartilage, inducing more severe osteoarthritic changes earlier in life. Because of variable conformational characteristics, the effect of exercise on expression of DJD in dogs with hip dysplasia is likely to be breed specific.

Although absolute thresholds do not exist in biology, the concept of a DI threshold, below which dogs are unlikely to develop DJD, is desirable, as it offers breeders an easily understood guideline for making important breeding decisions. Receiver operating characteristic curves allow evaluation of the specificity and sensitivity of using the DI to predict whether dogs would have DJD.[16] In the present study, such curves permitted us to calculate threshold DI with a sensitivity of 100% (ie, no dogs with DI less than the threshold values had DJD). Maximizing sensitivity inevitably decreases specificity (ie, the ability to determine with accuracy the dogs that will get DJD) to some extent; however, we believe that specificity is of lesser importance when the overall aim is to improve the gene pool by selecting against dogs with excessive hip joint laxity and a predisposition to develop DJD. Also, as discussed previously, the expression of DJD can be highly influenced by environmental factors. For German Shepherd Dogs, Golden Retrievers, Labrador Retrievers, and Rottweilers, the threshold levels of DI where the sensitivity is 100% (sensitivity and negative predictive value = 1) are 0.28, 0.32, 0.38, and 0.35, respectively. Below these levels, there were no false negative results within the age interval of this population. It should be emphasized that for practical reasons these values do not represent absolute thresholds, above which dogs should not be bred, because in some breeds, only a relatively small proportion of dogs will have DI lower than these thresholds. Rather, these thresholds represent ultimate breeding objectives for each breed. A clinically practical recommendation to effect genetic change toward better hip phenotype consists of breeding dogs that have a DI below the median DI for that breed. Use of dogs with the lowest DI in each breed (ie, imposing greater selection pressure) would result in more rapid genetic improvement on a per generation basis, but such a strategy in some popular breeds of dogs would be associated with undesirable genetic bottlenecks and may not be acceptable to breeders. Another strategy to enhance the rate of genetic improvement is to discontinue the common practice of mass selection (selecting breeding candidates solely on the basis of their individual phenotypes) and instead incorporate the DI of relatives (ie, pedigree information) into a calculation of breeding value of the individual sire or dam. Unfortunately, few kennels and databases have compiled the necessary information to carry out breeding-value calculations.

The DJD-susceptibility curves generated in the present study represent population data, and one cannot state with absolute certainty whether an individual dog will develop DJD. For all 4 breeds in the present study, the probability that a dog would have DJD increased as DI increased, but only in the German Shepherd Dog did the probability that a dog would have DJD approach 1 (DI > 0.9), indicating that all dogs with DI this high or higher would be likely to have DJD by a mean age of 38.1 months. This needs to be kept in mind by those suggesting that DI can be used to determine whether to perform surgery to prevent development of DJD.[17,18,c,d] Treatments purporting to prevent DJD require evaluation of age, breed, and DI-matched dogs to determine efficacy. In addition, the enthusiasm to perform surgical procedures to prevent DJD should be tempered by an understanding that mild to moderate DJD often causes mild or no clinical abnormalities in dogs.

[a] Smith GK, Biery DN, Iriye A, et al. Frequency of hip dysplasia in Golden Retrievers and Rottweilers and the effect of prescreening of radiographs on reported CHD prevalence figures (abstr), in *Proceedings*. Vet Ortho Soc Annu Conf 1997;61.
[b] SAS, version 8.0, SAS Institute, Cary, NC.
[c] Dueland RT, Patricelli AJ, Adams WM, et al. Juvenile pubic symphysiodesis on dysplastic puppies: 34 cases (abstr), in *Proceedings*. Vet Ortho Soc Annu Conf 2001;10.
[d] Bertram S. New hip dysplasia technique holds promise (abstr). *Vet Pract News* 2000;12:28.

References

1. Bouw J. Hip dysplasia and dog breeding. *Vet Q* 1982;4:173–181.
2. Kealy RD, Lawler DF, Ballam JM, et al. Evaluation of the effect of limited food consumption on radiographic evidence of osteoarthritis in dogs. *J Am Vet Med Assoc* 2000;217:1678–1680.
3. Kealy RD, Lawler DF, Ballam JM, et al. Five-year longitudinal study on limited food consumption and development of osteoarthritis in coxofemoral joints in dogs. *J Am Vet Med Assoc* 1997;210:222–225.
4. Reed AL, Keller GG, Vogt DW, et al. Effect of dam and sire qualitative hip conformation on progeny hip conformation. *J Am Vet Med Assoc* 2000;217:675–680.
5. Swenson L, Audell L, Hedhammar A. Prevalence and inheritance of and selection for hip dysplasia in seven breeds of dogs in Sweden and benefit: cost analysis of a screening and control program. *J Am Vet Med Assoc* 1997;210:207–214.
6. Fluckiger M, Lang J, Binder H, et al. Bekampfung der Huftgelenkdysplasie in der Schweiz. Ein Ruckblick auf die vergangenen 24 Jahre. *Schweiz Arch Tierheilkd* 1995;137:243–250.
7. Smith GK, Gregor TP, Rhodes WH, et al. Coxofemoral joint laxity from distraction radiography and its contemporaneous and prospective correlation with laxity, subjective score, and evidence of degenerative joint disease from conventional hip-extended radiography in dogs. *Am J Vet Res* 1993;54:1021–1042.
8. Smith GK, LaFond E, Gregor TP, et al. Within- and between-examiner repeatability of distraction indices of the hip joints in dogs. *Am J Vet Res* 1997;58:1076–1078.
9. Smith GK, Popovitch CA, Gregor TP, et al. Evaluation of risk factors for degenerative joint disease associated with hip dysplasia in dogs. *J Am Vet Med Assoc* 1995;206:642–647.
10. Popovitch CA, Smith GK, Gregor TP, et al. Comparison of susceptibility for hip dysplasia between Rottweilers and German Shepherd dogs. *J Am Vet Med Assoc* 1995;206:648–650.
11. Smith GK, Biery DN, Gregor TP. New concepts of coxofemoral joint stability and the development of a clinical stress-radiographic method for quantitating hip joint laxity in the dog. *J Am Vet Med Assoc* 1990;196:59–70.
12. Kealy RD, Olsson SE, Monti KL, et al. Effects of limited food consumption on the incidence of hip dysplasia in growing dogs. *J Am Vet Med Assoc* 1992;201:857–863.
13. Smith GK. Advances in diagnosing canine hip dysplasia. *J Am Vet Med Assoc* 1997;210:1451–1457.
14. Morgan JP. Canine hip dysplasia: significance of early bony spurring. *Vet Radiol* 1987;28:2–5.
15. Riser WH, Shirer JF. Correlation between canine hip dysplasia and pelvic muscle mass: a study of 95 dogs. *Am J Vet Res* 1967;28:769–777.
16. Hanley JA, McNeil BJ. The meaning and use of the area under a receiver operating characteristic (ROC) curve. *Radiology* 1982;143:29–36.
17. Mathews KG, Stover SM, Kass PH. Effect of pubic symphysiodesis on acetabular rotation and pelvic development in guinea pigs. *Am J Vet Res* 1996;57:1427–1433.
18. Slocum B, Slocum TD. Hip. In: Bojrab M, Ellison GW, Slocum B, eds. *Current techniques in small animal surgery*. 4th ed. Baltimore: The Williams & Wilkins Co, 1998;1127–1185.