Influence of trial repetition on lameness during force platform gait analysis in a heterogeneous population of clinically lame dogs each trotting at its preferred velocity

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OBJECTIVE
To determine variance effects influencing ground reaction forces (GRFs) in a heterogeneous population of lame dogs during trotting.

ANIMALS
30 client-owned dogs with thoracic limb lameness and 31 dogs with pelvic limb lameness.

PROCEDURES
GRFs, velocity, height at the dorsal aspect of the scapulae (ie, withers), and shoulder height were obtained. Each dog was trotted across a force platform at its preferred velocity. Variance effects for 12 velocity and associated relative velocity (V*) ranges were examined.

RESULTS
Individual dog, velocity, V*, and limb significantly influenced GRFs. Withers height V* ranges were associated with small variance in GRFs, but all absolute and V* ranges were associated with significant effects for all 4 limbs and both types of lameness. Significant changes in lame limb GRFs and velocity in ipsilateral trials in dogs with thoracic limb and pelvic limb lameness were evident with trial repetition. Withers height V* range of 0.55 to 0.93 captured a large proportion of trials (>90%) in dogs with thoracic limb or pelvic limb lameness, with limited effects on peak vertical force and vertical impulse.

CONCLUSIONS AND CLINICAL RELEVANCE
Trial repetition caused alterations to GRFs and subject velocity that may have confounded assessment of lameness, which supported the concept that a priori selection of a velocity or V* range for force platform gait analysis should use a range that captures valid trials efficiently while minimizing GRF variance. These ranges typically would span the preferred velocity of subject dogs, such as withers height V* of 0.55 to 0.93. (Am J Vet Res 2017;78:1284–1292)

Ground reaction forces obtained by use of force platform gait analysis are an important objective outcome measurement in canine clinical trials. The PVF and VI correlate with lameness severity. The PVF represents the maximal load exerted by a paw during the stance phase, whereas VI represents the area under the force-time curve. Vertical GRFs have been used in clinical trials to evaluate medical or surgical treatment (eg, stifle joint stabilization in dogs with cruciate ligament rupture) as an adjunct to subjective assessments such as orthopedic examinations and radiography.

The ideal approach for measurement of GRFs in lame dogs remains unclear. Breed size and conformation, velocity, trial repetition, and day-to-day changes may influence GRFs. Normalization of GRFs to body weight and the use of narrow velocity ranges (±0.3 m/s) with controlled acceleration (±0.5 m/s²) have been recommended to minimize data variance, as determined on the basis of studies in small homogeneous populations of clinically normal dogs that often represented specific breeds. This approach has been used in clinical trials of heterogeneous populations of lame dogs. However, larger numbers of trials are needed to obtain valid data with this approach, particularly when dogs are required to trot outside of their preferred velocity.

Dog populations used in clinical trials are heterogeneous. There is considerable variability in GRFs when comparing dogs of different body weights or conformation. To obtain comparable GRF values for dogs of differing morphology, researchers must account for variance associated with body weight.

ABBREVIATIONS
%BW Percentage of body weight
GRF Ground reaction force
PVF Peak vertical force
V* Relative velocity
VI Vertical impulse

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body shape, and velocity. On the basis of the theory of dynamic similarity, V* (ie, Froude number) is a unitless value in which velocity is rescaled to body size by use of height at the most dorsal aspect of the scapulae (ie, withers) or height at the shoulder. When dogs with differing conformation are trotted over a force plate, it may be preferable to measure GRFs by evaluating each individual dog at its preferred velocity, such that dogs are evaluated at a consistent V* or V* range.

Selection of specific velocity ranges influences trial repetition and efficient acquisition of valid trials because differences in dog morphology, disease, and body condition may affect a dog’s ability to walk or trot at a predetermined velocity. Gait analysis performed at a trot is more sensitive than is gait analysis performed at a walk for lameness evaluation, consequently, gait analysis at a trot is more commonly performed. In studies of heterogeneous lame canine populations, excessive trial repetition alters GRFs as a result of exercise-induced gait change and may ultimately limit collection of valid trials. Use of wider ranges for trotting velocity can improve efficiency of trial capture with little effect on PVF and VI variance in heterogeneous canine populations without lameness. Poor trial capture could exacerbate lameness such that insufficient valid trials are available for data analysis. This can occur for a variety of reasons, including dog temperament, handler variability, severity of lameness, and variation in force platform equipment. To collect an adequate number of valid trials for dogs with more severe lameness and limited mobility, velocity ranges for walking may be needed. There are also ethical considerations when requiring dogs that tire rapidly to trot or walk outside of their preferred velocity. Currently, the optimal trial velocity range and its impact on lameness with continued trial repetition are not known. The study reported here was designed to address this gap and refine the manner by which velocity is considered in collection and analysis of GRF data.

Therefore, the purpose of the study reported here was to determine variance effects for subject, trial velocity, and trial repetition on PVF and VI in a heterogeneous population of lame dogs at a trot. Variance effects for 12 velocity ranges and 7 V* ranges were analyzed. We hypothesized that trial repetition would result in significant effects on GRFs. We also hypothesized that narrow velocity ranges would be associated with lower variance but would capture trials inefficiently.

Materials and Methods

Animals

Medium- to large-breed client-owned dogs with orthopedic disease were recruited for the study. A veterinarian at the UW Veterinary Care Hospital examined each dog, and force platform gait analysis was then performed. Dogs were included if an orthopedic abnormality and mild to moderate lameness were identified in a single limb. Lameness was graded on a 5-point scale: grade 1 = mild lameness, grade 2 = moderate partial weight-bearing lameness with normal stride length, grade 3 = moderate partial weight-bearing lameness with shorter stride length, grade 4 = severe toe-touching lameness with minimal limb use, and grade 5 = non-weight-bearing lameness. Lameness in a limb was based on clinical signs of pain, crepitation, and altered joint range of motion. A clinical diagnosis of lameness was supported by radiographic or CT signs of joint disease. Withers height was measured at the dorsal aspect of the scapulae, and shoulder height was measured at the point of the proximal humerus bilaterally.

Then, PVF and VI of thoracic limb and pelvic limb pairs were examined to determine inclusion or exclusion. The PVF and VI for 5 trials of the left and right limb pairs obtained at velocities that most closely approximated the mean for each dog were analyzed by use of Student’s t tests for paired data. Differences were considered significant at P < 0.05. A symmetry index was calculated for the lame and contralateral limb pair. The symmetry index evaluated weight bearing between 2 limbs as symmetric (0) or asymmetric (index > 0 < index). The equation used was as follows: symmetry index = 200 × ([PVF1 – PVF2]/[PVF1 + PVF2]), where PVF1 is the higher PVF value and PVF2 is the lower PVF value for the pair. Dogs were excluded when the symmetry index was < 15%, a significant difference in PVF was not detected in the lame limb pair, clinical lameness was not confirmed by GRF data, or the dog could not complete at least 15 trials. Graphs of GRF data were examined to determine correlation with the clinically lame limb.

Initially, 88 dogs were identified for possible inclusion. Twenty-seven dogs were excluded, and data for the remaining dogs with thoracic limb (n = 50) or pelvic limb (31) lameness were analyzed further. The study was approved by the Animal Care and Use Committee of the University of Wisconsin-Madison School of Veterinary Medicine (protocols No. V1070, V1600, V5463, and V5488).

Force platform gait analysis

Trials were conducted by use of a single platform that measured 3-D forces and impulses. Velocity was measured by 3 photoelectric cells mounted at intervals of 1 m. A handler guided each dog across the platform at the dog’s preferred trotting velocity; all handlers were experienced with gait analysis methods. An observer evaluated each trial to confirm foot strikes and gait. A successful trial was defined by a thoracic limb hitting the platform followed by the ipsilateral pelvic limb hitting the platform with acceleration of ± 0.5 m/s² at a trot. Dogs were habituated to the force platform, and 15 to 40 trials were collected for each dog.

The force platform was connected to a data acquisition system and a computer with gait analysis software to perform mathematical calculations and produce tabular and graphical output. Gait analysis was performed at a walk for lameness evaluation or trot at a predetermined velocity. Gait analysis performed at a trot is more sensitive than is gait analysis performed at a walk for lameness evaluation, Consequently, gait analysis at a trot is more commonly performed. In studies of heterogeneous lame canine populations, excessive trial repetition alters GRFs as a result of exercise-induced gait change and may ultimately limit collection of valid trials. Use of wider ranges for trotting velocity can improve efficiency of trial capture with little effect on PVF and VI variance in heterogeneous canine populations without lameness. Poor trial capture could exacerbate lameness such that insufficient valid trials are available for data analysis. This can occur for a variety of reasons, including dog temperament, handler variability, severity of lameness, and variation in force platform equipment. To collect an adequate number of valid trials for dogs with more severe lameness and limited mobility, velocity ranges for walking may be needed. There are also ethical considerations when requiring dogs that tire rapidly to trot or walk outside of their preferred velocity. Currently, the optimal trial velocity range and its impact on lameness with continued trial repetition are not known. The study reported here was designed to address this gap and refine the manner by which velocity is considered in collection and analysis of GRF data.
software. Data were sampled at 1,000 Hz without filtering. The PVF and VI were measured and normalized on the basis of %BW. The PVF was normalized by use of the following equation: PVF_{SBW} = 100 × (PVF/[mg]), where m is body mass in kilograms, and g is gravitational acceleration (9.81 m/s²). The VI was normalized by use of a similar equation as follows: VI_{SBW} = 100 × (VI/[mg]). The value for V* (Froude number) was calculated for each trial by use of the following equation⁶: V* = V/(g×H)^{0.5}, where V is the velocity in meters per second, and H represents the withers height or shoulder height in meters.

### Selection of V* range

Trials were reviewed, and valid trial data were coded for ≥ 1 velocity ranges that had been used in other studies.⁵ ⁻⁷, ²¹ ⁻²⁸ ²⁸ The value for V* (Froude number) was calculated for each trial by use of the following equation⁶: V* = V/(g×H)^{0.5}, where V is the velocity in meters per second, and H represents the withers height or shoulder height in meters.

### Statistical analysis

Initially, a repeated-measures ANCOVA was used for analysis conducted by use of computer software.⁴ Factors included in the model were dog, trial number, limb (lame limb or contralateral limb), and velocity or V* treated as a covariate. Interaction between trial repetition and limb were also considered because lame and contralateral limbs were likely to have different behaviors with trial repetition. Histogram plots were used to examine the distribution of dependent variable data. Thoracic limb and pelvic limb data were analyzed separately. Variance effects for dog, trial number, limb, and velocity or V* were determined. Subsequently, variance effects of the velocity or V* ranges of interest were examined in the statistical model. Factor effect sizes were calculated.

We did not expect that all trial means for a GRF would be equal; therefore, post hoc analysis was performed by use of the Duncan test to compare first and last trials in the lame and contralateral limbs. Linear regression and scatterplots were also used to evaluate the relationship between GRFs or velocity and trial repetition. Data were reported as mean ± SD. Results were considered significant at P < 0.05.

### Results

#### Dogs

Data for 30 dogs with thoracic limb lameness and 31 dogs with pelvic limb lameness were analyzed. All dogs were > 1 year old. Mean ± SD body weight was 34.9 ± 10.5 kg (range, 19.7 to 62.6 kg). Breeds included were Labrador Retriever (n = 15), Golden Retriever (6), Border Collie (i), American Staffordshire Terrier (3), American Bulldog (2), Australian Shepherd (2), Boxer (2), and 1 each of Bernese Mountain Dog, Brittany Spaniel, Dalmatian, German Shepherd Dog, Greater Swiss Mountain Dog, English Springer Spaniel, Mastiff, Old English Sheepdog, Rottweiler, Samoyed, Shiba Inu, and Weimaraner; the remainder were mixed-breed dogs (15). There were 29 neutered males, 5 sexually intact males, and 27 spayed females. Of the 61 dogs, 8 had grade 1 lameness, 21 had grade 2 lameness, 12 had grade 3 lameness, and 20 had an unknown lameness score. Causes of thoracic limb lameness included elbow joint dysplasia (n = 22), carpal joint tendonitis (1), shoulder joint osteochondrosis dissecans (1), and an unknown diagnosis (6). Causes of pelvic limb lameness included cruciate ligament rupture after stifle joint stabilization surgery (n = 9), partial or complete cranial cruciate ligament rupture (15), tarsal joint osteoarthritis secondary to osteochondritis dissecans (2), medial patellar luxation (1), capital physeal fracture (1), and an unknown diagnosis (3). For the 30 dogs with thoracic limb lameness, withers height and shoulder height were measured in 29 and 28 dogs, respectively. For the 31 dogs with pelvic limb lameness, withers height and shoulder height were measured in 22 and 21 dogs, respectively. Analysis of GRFs confirmed the clinical observation of thoracic limb and pelvic limb lameness in all study dogs (Figures 1 and 2).

#### Effect of velocity and V* ranges on vertical GRFs

Mean ± SD velocity was 1.82 ± 0.22 m/s, mean withers height V* was 0.76 ± 0.11, and mean shoul-
der height $V^*$ was $0.89 \pm 0.13$ for thoracic limb lameness. Mean velocity was $1.84 \pm 0.23$ m/s, mean withers height $V^*$ was $0.77 \pm 0.11$, and mean shoulder height $V^*$ was $0.92 \pm 0.12$ for pelvic limb lameness. Analysis of effect sizes in lame dogs revealed that dog generally was the factor with the greatest variance in the model; the relative contribution of limb, velocity or $V^*$, and trial repetition to variance was variable (Table 1; Supplementary Tables S1 and S2, available at avmajournals.avma.org/doi/suppl/10.2460/ajvr.78.11.1284). Dog, limb, and velocity or $V^*$ had significant effects on PVF and VI for both limb pairs in dogs with thoracic limb and pelvic limb lameness. Limb-trial interactions were not significant.

All ranges were associated with significant effects on GRFs. Narrow velocity ranges were not consistently associated with lower variance (Tables 2 and 3; Supplementary Table S3, available at avmajournals.avma.org/doi/suppl/10.2460/ajvr.78.11.1284). For thoracic limb lameness, velocity ranges of 1.3 to 1.9, 1.5 to 2.0, 1.3 to 2.1, and 1.5 to 2.2 m/s; withers height $V^*$ ranges of 0.6 to 0.9, 0.7 to 0.93, 0.55 to 0.93, and 0.6 to 0.95; and shoulder height $V^*$ ranges of 0.8 to 1.05 and 0.7 to 1.2 were associated with low variance and few significant effects on GRFs. Of these ranges, velocity of 1.5 to 2.2 m/s, withers height $V^*$ of 0.55 to 0.93, and shoulder height $V^*$ of 0.7 to 1.2 captured the largest proportion of trials (Tables 4 and 5; Supplementary Tables S4 and S5, available at avmajournals.avma.org/doi/suppl/10.2460/ajvr.78.11.1284). For pelvic limb lameness, velocity ranges of 1.3 to 1.9 m/s and 1.3 to 2.1 m/s, withers height $V^*$ ranges of 0.55 to 0.93 and 0.6 to 0.95, and shoulder height $V^*$ ranges of 0.8 to 1.05, 0.7 to 1.2, and 0.65 to 1.05 were associated with low variance and few significant effects. Of these ranges, velocity of 1.3 to 2.1 m/s, withers height $V^*$ of 0.6 to 1.05, and shoulder height $V^*$ of 0.7 to 1.2 captured the largest proportion of trials.

**Trial repetition effects**

Trial number had no significant effect on thoracic limb lameness but significantly influenced thoracic limb VI for pelvic limb lameness in the withers height $V^*$ and shoulder height $V^*$ models (Table 1; Supplementary Tables S1 and S2). Comparison of the first and last trials for thoracic limb lameness revealed that PVF in the contralateral thoracic limb was higher, but not significantly so ($P = 0.09$), with trial repetition. When the first and last trials for dogs with pelvic limb lameness were compared, thoracic limb PVFs were significantly

![Figure 2](image)

**Figure 2**—Influence of trial repetition on PVF (A and C) and VI (B and D) of the lame (black squares) and contralateral non-lame (white squares) thoracic (A and B) and pelvic (C and D) limbs of 31 dogs with pelvic limb lameness. Each symbol represents the mean value for that trial number.

**Table 1**—Variance effects of model factors on PVF and VI of thoracic and pelvic limbs of dogs with thoracic limb (n = 30) and pelvic limb (31) lameness.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Thoracic limb PVF</th>
<th>Thoracic limb VI</th>
<th>Pelvic limb PVF</th>
<th>Pelvic limb VI</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>ES 95% CI</td>
<td>ES 95% CI</td>
<td>ES 95% CI</td>
<td>ES 95% CI</td>
</tr>
<tr>
<td>Thoracic limb lameness</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dog</td>
<td>0.7280† 0.6832–0.7438</td>
<td>0.5434† 0.4738–0.5671</td>
<td>0.7114† 0.6642–0.7281</td>
<td>0.6332† 0.5749–0.6536</td>
</tr>
<tr>
<td>WHV*‡</td>
<td>0.1436† 0.0968–0.1936</td>
<td>0.1439† 0.0971–0.1940</td>
<td>0.1715† 0.1216–0.2232</td>
<td>0.1487† 0.1013–0.1990</td>
</tr>
<tr>
<td>Lame limb</td>
<td>0.1436† 0.0968–0.1936</td>
<td>0.1439† 0.0971–0.1940</td>
<td>0.1715† 0.1216–0.2232</td>
<td>0.1487† 0.1013–0.1990</td>
</tr>
<tr>
<td>Limb-trial interaction</td>
<td>0.0360 0–0.0188</td>
<td>0.0360 0–0.0223</td>
<td>0.0317 0–0.0120</td>
<td>0.0285 0–0.0067</td>
</tr>
<tr>
<td>Trial number</td>
<td>0.0643 0–0.0523</td>
<td>0.0643 0–0.0333</td>
<td>0.0364 0–0.0121</td>
<td>0.0295 0–0.0006</td>
</tr>
<tr>
<td>Pelvic limb lameness</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dog</td>
<td>0.5997† 0.5302–0.6270</td>
<td>0.4080† 0.3177–0.4419</td>
<td>0.5446† 0.4679–0.5745</td>
<td>0.2613† 0.1663–0.2932</td>
</tr>
<tr>
<td>WHV*‡</td>
<td>0.3631† 0.2982–0.4211</td>
<td>0.4473† 0.3851–0.5017</td>
<td>0.1011† 0.0556–0.1539</td>
<td>0.1185† 0.0695–0.1734</td>
</tr>
<tr>
<td>Lame limb</td>
<td>0.0009 0–0.0138</td>
<td>0.0407† 0.0131–0.0805</td>
<td>0.4282† 0.3651–0.4838</td>
<td>0.4539† 0.3722–0.4901</td>
</tr>
<tr>
<td>Limb-trial interaction</td>
<td>0.0500 0–0.0247</td>
<td>0.0500 0–0.0293</td>
<td>0.0209 0–0.0000</td>
<td>0.0348 0–0.0006</td>
</tr>
<tr>
<td>Trial number</td>
<td>0.2016† 0.0796–0.1999</td>
<td>0.3449† 0.2254–0.3558</td>
<td>0.1024 0–0.0805</td>
<td>0.1255† 0.0118–0.0199</td>
</tr>
</tbody>
</table>

†Variance effect was significant ($P < 0.05$). ‡Calculated by use of the following equation: $V/((gH)^{0.5})$, where $V$ is the velocity in meters per second, $g$ is the gravitational acceleration (9.81 m/s²), and $H$ is the withers height in meters.

CI = Confidence interval. ES = Effect size. WHV* = Withers (ie, most dorsal aspect of the scapulae) height $V^*$.  

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increased after trial repetition and velocity was significantly decreased. In addition, PVF in the lame pelvic limb was higher, but not significantly so ($P = 0.07$), with repetition (Figure 3).

Use of linear regression analysis revealed no significant effects on GRFs for thoracic limb lameness with trial repetition. Velocity, but not $V^*$, was significantly ($R^2 = 0.04; P < 0.001$) decreased with trial repetition in the ipsilateral trials, and the fitted regression line had a negative slope. For pelvic limb lameness, trial repetition significantly influenced ipsilateral (PVF, $R^2 = 0.01; \ VI$, $R^2 = 0.04$) and contralateral (PVF, $R^2 = 0.01; \ VI$, $R^2 = 0.04$) thoracic limb PVF ($P < 0.05$) and VI ($P < 0.001$) and contralateral pelvic limb VI ($R^2 = 0.01; P < 0.05$) with increased GRFs, and the fitted regression lines had a positive slope (Figure 2). Trial repetition for pelvic limb lameness led to significant decreases in velocity (lame limb, $R^2 = 0.02$; contralat-

<table>
<thead>
<tr>
<th>Table 2—Variance effects for WHV* ranges and absolute velocity ranges with trial capture efficiencies of &gt; 60% on PVF and VI of thoracic and pelvic limbs of 30 dogs with thoracic limb lameness.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Factor</strong></td>
</tr>
<tr>
<td>WHV* ranges</td>
</tr>
<tr>
<td>Dog</td>
</tr>
<tr>
<td>Trial number</td>
</tr>
<tr>
<td>Ranged</td>
</tr>
<tr>
<td>0.6–0.9</td>
</tr>
<tr>
<td>0.7–0.93</td>
</tr>
<tr>
<td>0.6–1.05</td>
</tr>
<tr>
<td>0.73–1.15</td>
</tr>
<tr>
<td>0.55–0.93</td>
</tr>
<tr>
<td>0.60–0.95</td>
</tr>
<tr>
<td>Absolute velocity ranges</td>
</tr>
<tr>
<td>Dog</td>
</tr>
<tr>
<td>Trial number</td>
</tr>
<tr>
<td>Range (m/s)</td>
</tr>
<tr>
<td>1.3–1.9</td>
</tr>
<tr>
<td>1.5–2.0</td>
</tr>
<tr>
<td>1.7–2.1</td>
</tr>
<tr>
<td>1.5–2.3</td>
</tr>
<tr>
<td>1.3–2.1</td>
</tr>
<tr>
<td>1.5–2.2</td>
</tr>
</tbody>
</table>

†Variance effect was significant ($P < 0.05$) for the lame limb. ‡Variance effect was significant ($P < 0.05$) for the contralateral limb. §Reported as Froude number.

See Table 1 for remainder of key.
Table 4—Trial capture and associated PVF and VI values for WHV* ranges and absolute velocity ranges in a heterogeneous population of 30 dogs with thoracic limb lameness.

<table>
<thead>
<tr>
<th>WHV* range†</th>
<th>Total No. of trials</th>
<th>Total trials per dog (%)</th>
<th>Total No. of lame limb trials</th>
<th>Lame thoracic limb PVF (%BW)</th>
<th>Lame thoracic limb VI (%BW)</th>
<th>Ipsilateral pelvic limb PVF (%BW)</th>
<th>Ipsilateral pelvic limb VI (%BW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6–0.9</td>
<td>480</td>
<td>63.6 ± 21.3</td>
<td>278</td>
<td>81.8 ± 15.7</td>
<td>87.9 ± 13.9</td>
<td>15.0 ± 1.9</td>
<td>67.8 ± 10.5</td>
</tr>
<tr>
<td>0.70–0.93</td>
<td>483</td>
<td>66.5 ± 29.1</td>
<td>221</td>
<td>65.0 ± 31.3</td>
<td>89.8 ± 14.7</td>
<td>14.5 ± 1.9</td>
<td>69.6 ± 10.9</td>
</tr>
<tr>
<td>0.73–0.95</td>
<td>432</td>
<td>59.5 ± 30.9</td>
<td>191</td>
<td>56.2 ± 34.3</td>
<td>90.4 ± 15.7</td>
<td>14.3 ± 2.0</td>
<td>71.1 ± 10.4</td>
</tr>
<tr>
<td>0.6–1.05</td>
<td>673</td>
<td>92.7 ± 16.2</td>
<td>316</td>
<td>92.9 ± 23.7</td>
<td>87.5 ± 15.1</td>
<td>14.7 ± 2.2</td>
<td>68.7 ± 10.4</td>
</tr>
<tr>
<td>0.73–1.15</td>
<td>457</td>
<td>62.9 ± 33.3</td>
<td>207</td>
<td>60.9 ± 37.1</td>
<td>89.7 ± 16.3</td>
<td>14.1 ± 2.3</td>
<td>71.5 ± 10.4</td>
</tr>
<tr>
<td>0.55–0.93</td>
<td>659</td>
<td>90.8 ± 16.9</td>
<td>303</td>
<td>89.1 ± 21.0</td>
<td>87.5 ± 15.4</td>
<td>14.9 ± 2.0</td>
<td>67.8 ± 10.7</td>
</tr>
<tr>
<td>0.60–0.95</td>
<td>653</td>
<td>89.9 ± 17.2</td>
<td>303</td>
<td>89.1 ± 25.2</td>
<td>88.1 ± 14.7</td>
<td>14.8 ± 2.1</td>
<td>68.5 ± 10.5</td>
</tr>
</tbody>
</table>

Effect of absolute velocity and V* ranges on trial capture

A total of 749 and 850 trials were obtained for thoracic limb and pelvic limb lameness, respectively, with 351 and 382 lame limb trials. For thoracic limb and pelvic limb lameness, the mean ± SD number of trials per dog was 25.0 ± 5.3 and 27.4 ± 5.5, respectively. A total of 726 and 572 trials were obtained with withers height data for thoracic limb and pelvic limb lameness, respectively. A total of 706 and 532 trials were obtained with shoulder height data for thoracic limb and pelvic limb lameness, respectively. In general, narrow velocity ranges captured a smaller proportion of trials per dog (Tables 4 and 5; Supplementary Tables S4 and S5). The velocity range that captured the greatest number of trials was 1.5 to 2.5 m/s (696/749 [92.9%] for thoracic limb lameness. See Table 4 for key.

See Table 4 for key.
and $788/850 \, (92.7\%)$ for pelvic limb lameness. The velocity range that captured the fewest number of trials was $2.0$ to $2.5 \, \text{m/s}$ ($158/749 \, (21.1\%)$ for thoracic limb lameness and $192/850 \, (22.6\%)$ for pelvic limb lameness). Six of 12 velocity ranges captured $>60\%$ of trials/dog ($1.3$ to $1.9$, $1.5$ to $2.0$, $1.7$ to $2.1$, $1.5$ to $2.5$, $1.3$ to $2.1$, and $1.5$ to $2.2 \, \text{m/s}$). Mean PFV and VI were variable across these ranges.

Trial capture by withers height $V^\circ$ ranges was similar to that for absolute velocity ranges (Tables 4 and 5; Supplementary Tables S4 and S5). The withers height $V^\circ$ range of $0.6$ to $1.05$ captured the greatest number of trials ($673/726 \, (92.7\%)$ for thoracic limb lameness and $557/572 \, (95.9\%)$ for pelvic limb lameness). The withers height $V^\circ$ range of $0.73$ to $0.95$ captured the fewest number of trials ($432/726 \, (59.5\%)$ for thoracic limb lameness and $370/572 \, (64.7\%)$ for pelvic limb lameness). All withers height $V^\circ$ ranges captured $>60\%$ of trials/dog, except for $0.73$ to $0.95$ for thoracic limb lameness. Mean PFV and VI were variable across all withers height $V^\circ$ ranges.

Trial capture by shoulder height $V^\circ$ ranges was similar to that for absolute velocity ranges (Supplementary Tables S4 and S5). The shoulder height $V^\circ$ range that captured the greatest number of trials was $0.7$ to $1.2$ ($652/706 \, (92.4\%)$ for thoracic limb lameness and $514/532 \, (96.6\%)$ for pelvic limb lameness). The shoulder height $V^\circ$ range that captured the fewest number of trials was $0.85$ to $1.1$ ($452/706 \, (64.0\%)$ for thoracic limb lameness and $0.7$ to $1.0 \, \text{m/s}$ ($397/532 \, (74.6\%)$) for pelvic limb lameness). All shoulder height $V^\circ$ ranges captured $>60\%$ of trials/dog. Mean PFV and VI were variable across all shoulder height $V^\circ$ ranges.

**Discussion**

The heterogeneous group of dogs used in the study reported here was similar to that used in another study. We intended to study a sample population representative of canine clinical trials. Consequently, age and body weight were not used as inclusion criteria. Limb had a significant effect on GRFs, which supported the clinical observations of lameness. Dogs were excluded when significant PFV asymmetry was not identified. The asymmetry cutoff was set at $>15\%$ for inclusion in the study to account for preference of weight bearing on the left or right limbs that may lead to mild asymmetry in weight bearing. Results for the present study were consistent with those in previous studies that identified dog morphology, velocity, and limb as sources of GRF variance. Data in the present study were normalized by use of %BW before analysis, as is typically performed. Morphometrical normalization of GRFs reduces variance but does not eliminate it entirely, and differences between breeds are still evident. In addition, gait variables were normalized on the basis of body size by use of withers height or shoulder height because use of breed- and age-matched control groups in veterinary medical clinical trials has low feasibility.

Velocity for a gait analysis trial is a predetermined aspect of experimental design. Overall, mean velocity or $V^\circ$ was similar for thoracic limb and pelvic limb lameness. In contrast to results for healthy dogs, whereby several velocity ranges had no significant effects on GRFs, all velocity ranges in the present study had a significant effect on GRFs in lame dogs. Narrow velocity and $V^\circ$ ranges captured fewer trials per dog, which was consistent with results for clinically normal dogs. However, several wider ranges for velocity and $V^\circ$ were associated with low variance and limited significant effects on GRFs. These ranges spanned the respective mean velocity or $V^\circ$. The withers height $V^\circ$ range of $0.55$ to $0.93$ captured trials efficiently with few significant effects on GRFs for dogs with both types of lameness. The shoulder height $V^\circ$ range of $0.7$ to $1.2$ yielded a similar result. Withers height can be measured more easily and consistently than can shoulder height, which is subject to variation in measurements between left and right limbs. Results reported here supported those for clinically normal dogs and suggested that it is advantageous to perform force platform gait analysis on lame dogs by use of individual velocity ranges calculated from a $V^\circ$ range that enables efficient trial capture while also minimizing GRF variance. Individual absolute velocity ranges can easily be calculated by use of the equation $V = V^\circ \cdot (g \cdot H)^{0.5}$, where $V$ is the velocity in meters per second, $g$ is the gravitational acceleration (9.81 m/s$^2$), and $H$ is the withers height in meters.

Exacerbation of lameness can occur with continued exercise. Dogs in the study reported here had a mild to moderate degree of lameness. Trial repetition influenced GRFs in these dogs, with mild alterations to the pattern of weight bearing and trotting velocity. Comparison of first and last trials revealed some shifting of weight to the contralateral thoracic limb (although not significant) for dogs with thoracic limb lameness and increased weight bearing in the thoracic limbs of dogs with pelvic limb lameness. Use of a linear regression model revealed increased weight
bearing in the thoracic limbs and contralateral pelvic limb for dogs with pelvic limb lameness, although the proportion of variance in GRFs and velocity explained by trial repetition was small (<5%). Taken together, these observations suggested that there were mild alterations in weight bearing with trial repetition, particularly for dogs with pelvic limb lameness. Such effects may be more evident with increasing lameness severity; dogs that could not complete at least 15 trials were excluded from the present study. It is possible that dogs with mild clinical signs of lameness may gradually improve with trial repetition because initial stiffness, such as that caused by osteoarthritis, can improve with exercise. However, preferred velocity and $V^*$ in the present study decreased with trial repetition, particularly for dogs with pelvic limb lameness, which suggested a decrease in mobility with trial repetition.21

Weight shifting and load redistribution are important in quadrupeds. Load redistribution has been evaluated with regard to subclinically affected dogs with radiographic evidence of osteoarthritis, and it was found to shift between pelvic limb pairs,14 whereas clinically lame dogs with signs of pain in the hip joints were found to shift weight to the thoracic limbs.32 Load redistribution with elbow joint osteoarthritis is reduced in the clinically lame limb and increased in the contralateral limb.33 Increased PVF in the contralateral pelvic limb after induction of stifle joint synovitis or transection of the cranial cruciate ligament has been identified.22,34

The present study had several limitations. Currently, a single force platform is most often used for gait analysis. However, a single force platform cannot measure consecutive footfalls during locomotion, thus necessitating additional trials to obtain data for the contralateral limb.10,35 Repetition of trials is reduced by use of multiple force platforms whereby GRFs from all 4 limbs are measured in 1 trial.10,15,36 A pressure walkway system,37,38 or an integrated treadmill.14,39 Multiple force platforms decrease the time required and number of trials needed to obtain valid data, compared with those required for single force platform systems.36,40 Multiple force platforms and pressure walkway systems are limited by variation in velocity, which may be addressed through use of an integrated treadmill system, whereby measurements are obtained for all 4 limbs simultaneously during constant velocity.14,39 As these systems become more widely used, their role in GRF data collection will need to be optimized.

Withers height and shoulder height were not measured in all dogs, and this may have affected the results. Ground reaction forces are susceptible to small nonspecific day-to-day variation.31 Repeated force platform sessions with these same dogs on different days or with different handlers may have been useful to further evaluate effects of trial repetition.8,11 Effects of trial repetition are likely to be more evident in dogs with severe lameness, but they may require analysis at a walking velocity because of the inability to complete trials at a trot as a result of reduced mobility. Dogs of the present study were affected by multiple orthopedic conditions. The impact of trial repetition on lameness may differ on the basis of the underlying disease, and it may have been helpful to investigate common orthopedic diseases (eg, cranial cruciate ligament rupture or hip joint and elbow joint dysplasia) separately. The study was limited to dogs with clinical lameness in a single limb; effects of trial repetition would likely be more complex in dogs with lameness in multiple limbs. In future studies of trial repetition, analysis of both invalid trials as a result of partial foot strikes as well as valid trials may be an important consideration. Other approaches to data analysis could also be considered, such as changes in the symmetry index attributable to trial repetition.

In the study reported here, a complex interplay of factors influenced GRF variance for force platform gait analysis, with dog being the greatest source of variance in a heterogeneous population. Trial repetition caused alterations to GRFs and subject velocity that may have confounded assessment of lameness, which provided support for the concept that a priori selection of a velocity or $V^*$ range for force platform gait analysis should consider use of a range that captures valid trials efficiently while minimizing GRF variance; such ranges would typically span the preferred velocity of the subject dogs. Use of individual velocity ranges created from the withers height $V^*$ range would be appropriate, and a withers height $V^*$ of 0.55 to 0.93 would be one such range.

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Footnotes

1. OR6-6-1000 biomechanics platform with SGA6-4 signal conditioner/amplifier, Advanced Mechanical Technologies, Phoenix, Ariz.
3. Eric Hans and Peter Muir, Comparative Orthopaedic Research Laboratory, School of Veterinary Medicine, University of Wisconsin, Madison, Wis: Unpublished data, 2014.
4. STATA, version 14.0, Stata Corp LP, College Station, Tex.
5. Voss K, Damur DM, Guerrero T, et al. Force plate gait analysis at a walking velocity because of the inability to complete trials at a trot as a result of reduced mobility. Dogs of the present study were affected by multiple orthopedic conditions. The impact of trial repetition on lameness may differ on the basis of the underlying disease, and it may have been helpful to investigate common orthopedic diseases (eg, cranial cruciate ligament rupture or hip joint and elbow joint dysplasia) separately. The study was limited to dogs with clinical lameness in a single limb; effects of trial repetition would likely be more complex in dogs with lameness in multiple limbs. In future studies of trial repetition, analysis of both invalid trials as a result of partial foot strikes as well as valid trials may be an important consideration. Other approaches to data analysis could also be considered, such as changes in the symmetry index attributable to trial repetition.

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