For a long time, force plate (FP) gait analysis has been used in veterinary science. Quantitative gait analysis is expected to enable the detection of mild lameness that is not visible and the verification of disease-specific gait patterns. FP gait analysis is commonly used to diagnose orthopedic diseases, can be used to objectively evaluate treatment outcomes for various orthopedic diseases, and has been used in clinical research. The sensitivity and specificity of the FP analysis of dogs are 93% and 94%, respectively, indicating that it is a useful diagnostic method. By obtaining repeatable data, it is possible to obtain objective, quantifiable, and accurate information regarding the normal or abnormal gait of dogs. Currently, the diagnosis of canine lameness tends to be subjective, because the interpretation of visual examination, which is the mainstream approach for gait analysis, is influenced by clinical and personal experience. Therefore, the application of a gait analysis system, such as FP, to evaluate individual cases of lameness is likely to be more clinically valuable. Various factors, such as velocity, acceleration, handler, weight, breed, physique, daily variation, number of trials, and habituation, may affect variations in the ground reaction force (GRF).

There have been many reports of GRFs in the vertical force (Fz) direction, such as peak vertical force (PVF) and vertical impulse (VI), and in the cranial or caudal force (Fy) direction, such as peak propulsive force (PPF), peak braking force (PBF), propulsive impulse (PI), braking impulse (BI), peak vertical force (PVF), and vertical impulse (VI). GRFs in the Fz direction have less variability and are most often used clinically, because the vertical force has to support the body weight.

OBJECTIVE
To evaluate changes in ground reaction forces (GRFs) in relation to gait velocity using 2 force plates (FPs) for healthy Beagles.

ANIMALS
18 healthy Beagles were included (body weight, 10.45 ± 1.28 kg; age, 26 ± 11 months).

PROCEDURES
Ten GRF parameters were measured at three gait velocities (walk, 0.9 to 1.2 m/s; trot 1, 1.6 to 2.0 m/s; and trot 2, 2.1 to 2.5 m/s): peak lateral force (PLF), peak medial force (PMF), lateral impulse (LI), medial impulse (MI), peak propulsive force (PPF), peak braking force (PBF), propulsive impulse (PI), braking impulse (BI), peak vertical force (PVF), and vertical impulse (VI).

RESULTS
As velocity increased, the PVF of all limbs increased, the VI of all limbs decreased, and the PPF of the forelimbs increased. At all velocities, PBF and BI were significantly higher than the PPF and PI in forelimbs; however, PBF and BI were significantly lower than the PPF and PI in hindlimbs. There were no significant differences in the PLF, PMF, LI, and MI of the forelimbs and hindlimbs among all velocities. The PLF was significantly higher than the PMF of forelimbs during trot 1 and trot 2.

CLINICAL RELEVANCE
These results may be useful when comparing healthy Beagles with diseased ones when premorbid data are not available. Because the forelimbs are mainly responsible for the braking force, it is suggested that weight bearing is more stable in the forelimbs than in the hindlimbs, which are mainly responsible for the propulsive force, and that a greater force is generated laterally than medially during trot.

Force plate analysis of ground reaction forces in relation to gait velocity of healthy Beagles

Tom Ichinohe, PhD1,2; Hiromi Takahashi, BVSc2; Yukihiro Fujita, PhD1,2*

1Department of Small Animal Orthopedic Surgery, Veterinary Teaching Hospital, Azabu University, Sagamihara-shi, Kanagawa, Japan
2Laboratory of Small Animal Surgery, Azabu University, Sagamihara-shi, Kanagawa, Japan
*Corresponding author: Dr. Fujita (fujita@azabu-u.ac.jp)
https://doi.org/10.2460/ajvr.22.03.0057

American Journal of Veterinary Research
show an increasing trend as the velocity increases, but the extent of variation is large and the reliability is low.\textsuperscript{18} Regarding GRFs in the Fx direction, significant differences and trends are often not detected, partly because the values are smaller than those of other parameters.\textsuperscript{10,17,18}

Most previous studies have evaluated the Fz direction in large dogs such as Greyhounds, Labrador Retrievers, and Rottweilers, whose body weight is often greater than 20 kg; however, only a few studies have evaluated small to medium dogs weighing around 10 kg\textsuperscript{2,4,7-10,12-15,17} and their GRFs in the Fx or Fy direction.\textsuperscript{3-9,12,13,15} In this study, 2 FP\textsubscript{s} were used to evaluate changes in GRFs in relation to gait velocity and differences in GRFs, including the Fx and Fy directions, among healthy Beagles, which are small dogs. It was hypothesized that a certain trend would be observed for GRFs in the Fx and Fy directions with 2 FP\textsubscript{s}.

Materials and Methods

Animals

Eighteen Beagles acquired by our institute as experimental animals that were determined to be healthy based on general physical, radiological, orthopedic, and neurological examination results were included. Experimental procedures for this study were reviewed and approved by the Animal Welfare and Ethics Committee of our institute.

Testing procedure

Two FP\textsubscript{\text{S}} (50.2 X 50.2 X 4.44 cm; Fz maximum load, 1,334 N; Fx/Fy maximum load, 450 N; AccuGait System; AMTI NetForce Advanced Mechanical Technology, Inc) placed next to each other were used for gait analysis. Two walking paths (90.9 X 159.0 X 4.44 cm; total length, 736.4 cm) were placed in front and behind the FP\textsubscript{\text{s}}. A frame with through-beam photoelectric sensors (5 pairs of photoelectric sensors; minimum detection diameter, 8 mm; distance between photoelectric sensors, 300 mm; E3Z-T81A; OMRON Corporation) was placed at both ends of the plate within 2.5 m of each other to measure walking time, velocity, and acceleration. The height of the transmissive photoelectric sensors from the ground was adjusted to the dorsal edge of the scapula when the dog was in a normal standing position.\textsuperscript{15} The sampling rate for the measurement using FP\textsubscript{\text{s}} was unified at 120 Hz per channel for 3 s. A video camera was fixed at a position where each dog’s limb on the 2 FP\textsubscript{\text{S}} could be observed, and the measurement process was recorded, identifying the forelimb that first contacted the plate and the hindlimb that last contacted the plate; forelimbs and hindlimbs that contacted the plate at the same time or partially contacted the plate were excluded from the data. The arrangement of the gait analysis system described above is shown in Figure 1. A handler walked the Beagles using a collar and lead on a stage. GRF data were collected and analyzed using motion analysis software (ToMoCo-FPm; Toso System, Inc).

Gait velocity

GRF was measured during the following three types of gait velocity: walk, 0.9 to 1.2 m/s; trot 1, 1.6 to 2.0 m/s; and trot 2, 2.1 to 2.5 m/s.\textsuperscript{13,14} An acceleration value of 0.5 m/s\textsuperscript{2} was considered valid.\textsuperscript{6,8}

Measured parameters

GRFs can be classified into medial or lateral (Fx), cranial or caudal (Fy), and vertical (Fz) forces during the stance time. The following 10 GRF parameters were measured: the force in the Fx direction, which includes the PLF, PMF, LI, and MI; the force in the Fy direction, which includes the PPF, PBF, PI, and BI; and the force in the Fz direction, which includes the PVF and VI.\textsuperscript{10,17,18} The PVF is the maximum load in the Fz direction during the stance phase. The VI is the area enclosed by the time and force curves in the Fz direction and represents the total force applied over the foot contact time.\textsuperscript{18} The PPF is the maximum propulsive force in the positive Fy direction during the stance phase. The PI is the area enclosed by the time and force curves in the positive Fy direction. The PBF is the maximum deceleration force in the negative Fy direction during the stance phase. The BI is the area enclosed by the time and force curves in the negative Fy direction.
The PLF is the maximum lateral reaction force in the negative Fx direction during the stance phase. The LI is the area enclosed by the time and force curves in the negative Fx direction. The PMF is the maximum medial reaction force in the positive Fx direction during the stance phase. The MI is the area enclosed by the time and force curves in the positive Fx direction. GRFs were measured at least 5 times for each limb at each velocity to obtain a valid value. Values for GRF parameters are presented as percentages of body weight (100 X N/N).

Stance and swing times were also confirmed using videos, measured waveforms, and vectors obtained at the time of measurement. The symmetry index (SI) was calculated for each parameter using the following formula:

\[ SI = \left( \frac{\text{GRFr} - \text{GRFl}}{\text{GRFr} + \text{GRFl}} \right) \times 100(\%) \]

where GRFr is the mean value of the right forelimb and hindlimb GRF and GRFl is the mean value of the left forelimb and hindlimb GRF. The SI shows the ratio of the difference between the left and right GRFs to the average of the left and right GRFs. The closer the SI to 0, the more symmetrical is the GRF. Parameters with an SI within 15% were considered symmetrical.

### Statistical analysis

Data analysis was performed using statistical software (BellCurve for Excel version 3.22; Social Survey Research Information Co, Ltd). The Shapiro-Wilk test was used to test data normality. The 95% confidence interval (CI) was set as the normal range for each GRF parameter. Parameters of forelimbs and hindlimbs were compared among velocities and at each velocity using 1-way analysis of variance for repeated measurements. The Tukey test was performed for parametric data during post hoc analyses. The Kruskal-Wallis test and Steel-Dwass test were performed for nonparametric data during post hoc analyses. Differences were considered significant at \( P < .05 \).

### Results

#### Animals

The body weight and age (mean ± standard deviation [SD]) of the Beagles were 10.45 ± 1.28 kg and 26 ± 11 months, respectively.

#### Values of parameters

The mean, SD, and upper and lower confidence limits of the 95% CI of each parameter, such as GRF, stance time, and swing time, at each gait velocity, are shown in Tables 1-3.

#### Symmetry index

The SIs for each GRF parameter at each gait velocity are listed in Table 4. All SIs in the Fy and Fz directions were less than 15%, indicating that they were symmetrical.

### Table 1—Mean, standard deviation, and upper and lower 95% confidence interval limits for ground reaction force (100 X N/N), stance time (s), and swing time (s) during walk.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>SD</th>
<th>UCL</th>
<th>LCL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2—Mean, standard deviation, and upper and lower 95% confidence interval limits for ground reaction force (100 X N/N), stance time (s), and swing time (s) during trot 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>SD</th>
<th>UCL</th>
<th>LCL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

See Table 1 for key.
Table 3—Mean, standard deviation, and upper and lower 95% confidence interval limits for ground reaction force (100 X N/N), stance time (s), and swing time (s) during trot 2.

<table>
<thead>
<tr>
<th></th>
<th>PVF</th>
<th>VI</th>
<th>PPF</th>
<th>PI</th>
<th>PBF</th>
<th>BI</th>
<th>PLF</th>
<th>LI</th>
<th>PMF</th>
<th>MI</th>
<th>Stance</th>
<th>Swing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forelimb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>130.774</td>
<td>10.600</td>
<td>8.345</td>
<td>0.379</td>
<td>17.938</td>
<td>0.870</td>
<td>12.598</td>
<td>0.911</td>
<td>4.232</td>
<td>0.271</td>
<td>0.139</td>
<td>0.196</td>
</tr>
<tr>
<td>SD</td>
<td>13.639</td>
<td>1.611</td>
<td>2.793</td>
<td>0.169</td>
<td>4.697</td>
<td>0.305</td>
<td>10.428</td>
<td>0.900</td>
<td>3.533</td>
<td>0.277</td>
<td>0.014</td>
<td>0.019</td>
</tr>
<tr>
<td>UCL</td>
<td>133.824</td>
<td>10.960</td>
<td>8.969</td>
<td>0.417</td>
<td>18.989</td>
<td>0.938</td>
<td>14.930</td>
<td>1.113</td>
<td>5.022</td>
<td>0.333</td>
<td>0.142</td>
<td>0.200</td>
</tr>
<tr>
<td>LCL</td>
<td>127.724</td>
<td>10.240</td>
<td>7.720</td>
<td>0.342</td>
<td>16.888</td>
<td>0.802</td>
<td>10.266</td>
<td>0.710</td>
<td>2.844</td>
<td>0.209</td>
<td>0.136</td>
<td>0.192</td>
</tr>
<tr>
<td>Hindlimb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>85.682</td>
<td>5.958</td>
<td>12.974</td>
<td>0.739</td>
<td>6.391</td>
<td>0.145</td>
<td>3.977</td>
<td>0.189</td>
<td>4.028</td>
<td>0.189</td>
<td>0.147</td>
<td>0.163</td>
</tr>
<tr>
<td>SD</td>
<td>12.317</td>
<td>0.974</td>
<td>3.946</td>
<td>0.304</td>
<td>4.435</td>
<td>0.094</td>
<td>2.997</td>
<td>0.157</td>
<td>2.459</td>
<td>0.147</td>
<td>0.018</td>
<td>0.145</td>
</tr>
<tr>
<td>UCL</td>
<td>88.436</td>
<td>6.176</td>
<td>13.856</td>
<td>0.807</td>
<td>7.361</td>
<td>0.166</td>
<td>4.648</td>
<td>0.224</td>
<td>4.578</td>
<td>0.222</td>
<td>0.151</td>
<td>0.195</td>
</tr>
<tr>
<td>LCL</td>
<td>82.928</td>
<td>5.740</td>
<td>12.091</td>
<td>0.671</td>
<td>5.621</td>
<td>0.124</td>
<td>3.307</td>
<td>0.154</td>
<td>3.478</td>
<td>0.156</td>
<td>0.143</td>
<td>0.130</td>
</tr>
</tbody>
</table>

See Table 1 for key.

Table 4—Symmetry index (%) for each ground reaction force parameter during each gait velocity.

<table>
<thead>
<tr>
<th></th>
<th>PVF</th>
<th>VI</th>
<th>PPF</th>
<th>PI</th>
<th>PBF</th>
<th>BI</th>
<th>PLF</th>
<th>LI</th>
<th>PMF</th>
<th>MI</th>
<th>Stance</th>
<th>Swing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walk</td>
<td>2.514</td>
<td>3.371</td>
<td>1.726</td>
<td>0.381</td>
<td>3.581</td>
<td>11.339</td>
<td>94.258</td>
<td>120.470</td>
<td>88.032</td>
<td>96.582</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trot 1</td>
<td>0.445</td>
<td>0.813</td>
<td>0.852</td>
<td>1.878</td>
<td>0.967</td>
<td>1.359</td>
<td>52.603</td>
<td>56.439</td>
<td>17.005</td>
<td>46.366</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

See Table 1 for key.

Table 5—P values of the comparisons of each parameter among the velocities and among all parameters at each velocity.

<table>
<thead>
<tr>
<th></th>
<th>PVF</th>
<th>VI</th>
<th>PPF</th>
<th>PBF</th>
<th>PI</th>
<th>BI</th>
<th>PLF</th>
<th>PMF</th>
<th>MI</th>
<th>Stance</th>
<th>Swing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forelimb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trot 1</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>.549</td>
<td>.974</td>
<td>.373</td>
<td>.993</td>
<td>1.000</td>
<td>.796</td>
</tr>
<tr>
<td>Trot 2</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>.938</td>
<td>.077</td>
<td>.122</td>
<td>.818</td>
<td>.984</td>
<td>.618</td>
</tr>
<tr>
<td>Trot 1</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>.938</td>
<td>.077</td>
<td>.122</td>
<td>.818</td>
<td>.984</td>
<td>.618</td>
</tr>
<tr>
<td>Trot 2</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>.938</td>
<td>.077</td>
<td>.122</td>
<td>.818</td>
<td>.984</td>
<td>.618</td>
</tr>
<tr>
<td>Trot 1</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>.938</td>
<td>.077</td>
<td>.122</td>
<td>.818</td>
<td>.984</td>
<td>.618</td>
</tr>
<tr>
<td>Trot 2</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>.938</td>
<td>.077</td>
<td>.122</td>
<td>.818</td>
<td>.984</td>
<td>.618</td>
</tr>
<tr>
<td>Trot 1</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>.938</td>
<td>.077</td>
<td>.122</td>
<td>.818</td>
<td>.984</td>
<td>.618</td>
</tr>
<tr>
<td>Trot 2</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>.938</td>
<td>.077</td>
<td>.122</td>
<td>.818</td>
<td>.984</td>
<td>.618</td>
</tr>
</tbody>
</table>

See Table 1 for key.

**Comparison of each parameter of the velocities and all parameters at each velocity**

The P values resulting from the comparisons of each parameter among the velocities and among all parameters at each velocity are shown in Table 5. PPFs were significantly higher in the forelimbs and hindlimbs during trot 1 and trot 2 than during walk. There were no significant differences in the PPFs of the limbs among all velocities. As the velocity increased, the PPF increased and the VI decreased.

There were significant differences in PPFs of the forelimbs among all velocities. PPFs of forelimbs were significantly higher during trot 1 and trot 2 than during walk. As the velocity increased, the PPF of the forelimbs increased. The PPFs of the hindlimbs were significantly higher during trot 1 and trot 2 than during walk. There were significant differences in the PPFs of the hindlimbs at all velocities. As the velocity increased, the PBF of the forelimbs increased. There were no significant differences in the PIs and BIs of the forelimbs and hindlimbs among all velocities. The PBFs and BIs were significantly higher than the PPFs and PIs of forelimbs at all velocities (P < .001). The PPFs and PIs were significantly higher than the PBFs and BIs of the hindlimbs at all velocities (P < .001).

There were no significant differences in the PLF, PMF, LI, and MI of forelimbs or hindlimbs among all velocities. The P values resulting from the comparisons of PLF versus PMF and LI versus MI at each velocity are shown in Supplementary Table S1. The PLF was significantly higher than the PMF of the forelimbs during trot 1 and trot 2. The LI was also significantly higher than the MI of the forelimbs during trot 1. However, no significant differences between the PLF and PMF or between the LI and MI of the hindlimbs were observed.

There were significant differences in the stance time among all velocities for both forelimbs and hindlimbs. As the velocity increased, the stance time decreased for both forelimbs and hindlimbs. The swing times were significantly shorter during trot 1 and trot 2 than during walk for the forelimbs. The swing times were significantly shorter during walk and trot 1 than during trot 2 for the hindlimbs.
However, there was no difference in swing times between trot 1 and trot 2 in forelimbs, or between walk and trot 1 in hindlimbs. The P values of the comparisons between stance versus swing time at each velocity are shown in Supplementary Table S2. The stance time was significantly longer than the swing time during walk in all limbs. However, this was reversed during trot 1 and trot 2, when the swing time was significantly longer than the stance time in all limbs.

**Discussion**

In the present study, the SI in the Fx direction was high, whereas the SIs in the Fy and Fz directions were low. As the gait velocity increased, the PVF increased and VI decreased in the forelimbs and hindlimbs. At all velocities, the PBF and BI were significantly higher than the PPB and PI in the forelimbs, whereas the opposite was observed in the hindlimbs. As the velocity increased, the PPB significantly increased in the forelimbs; this tendency was also observed in the hindlimbs. However, there was no difference among PIs at all velocities. As the velocity increased, the PBF significantly increased in the hindlimbs; this tendency was also observed in forelimbs. In contrast, there was no difference among the BIs at all velocities. There was no significant difference among all parameters in the Fx direction at all velocities. However, the PLF was significantly higher than the PMF in the forelimbs during trot 1 and trot 2.

Among different breeds, differences exist in body weight, limb length, height, physique, and gait. Moreover, it is better to walk dogs with different physiques at similar relative velocities, rather than absolute velocities, when performing a comparative study of various breeds. In previous studies, the standardization of the velocity according to physique and other factors was considered. Although standardization of the velocity according to physique and other factors was not performed during the present study, the results may be useful when comparing healthy Beagles with Beagles with diseases when premorbid data are not available.

Since gait velocity affects GFR variability, the approximate gait velocity allows for more accurate GFR measurements. The number of walking trials decreases when 2 FPs, rather than 1, are used; therefore, it is possible to suppress the variation in GFR caused by trial repetition. Therefore, during this study, the fluctuations in GFR might have been small. Although a single FP is more widely used, the use of 2 FPs can reduce the number of trials and the measurement time required to collect consistent and reproducible data. This would reduce the possibility of worsening of lameness or GFR variations caused by excessive repetition of trials.

Because the SI is used clinically to evaluate changes before and after improvement in lameness, it is recommended that variance should be minimized. The SI can be used to detect lameness because limb symmetry is expected to change with the presence of lameness attributable to the force distribution pattern. Moreover, the SI is lower when 2 FPs, rather than 1, are used, and it is possible to reduce the variation in GFRs attributable to the repetition of trials. During this study, the PVF and VI were within the symmetrical range (< 15%) at all velocities. The SI was also calculated for parameters included in Fx and Fy directions. The PPF, PI, PBF, and BI were also within the symmetrical range at all gait velocities. The SIs of GFRs in the Fx direction were outside the symmetrical range. The SI has been assessed most accurately with PVF, and the VI has been considered valid; moreover, it has been considered inappropriate to assess the SI with other parameters. However, the results of the present study showed that GFRs included in the Fy direction were also within the symmetrical range. This was because the symmetrical range was set to be relatively wide (0% to 15%). If the sample size is further increased, it is possible to investigate the range in which the SI is closer to 0%, such as 6%. Even when the symmetrical range was set to 0% to 6%, the PVF, VI, PPF, and PI values obtained at all velocities were within the symmetrical range. It has been suggested that the SI is more accurately evaluated with the PVF, VI, PPF, and PI than with the PBF, BI, and GFRs in the Fx direction. Even for a healthy dog, equal weight loading to the left and right sides during walking is not considered easy; furthermore, if even one GFR parameter is asymmetrical, it is not regarded as abnormal, even if the SI is high. However, it was also suggested that forces would be not distributed evenly in this study. When evaluating treatment outcomes of dogs with mild hindlimb lameness and healthy dogs, an assessment of the SI during trot is more sensitive and accurate than that during walk. The SI values were closer to 0 and more symmetrical during trot than during walk in this study. This is because trot 1 is an efficient gait for healthy dogs because it has a certain speed, which lowers the energy loss to the left and right, and is suitable for prolonged movement. However, walking involves a relatively slow gait; therefore, the weight load is not stable and tends to be asymmetrical, and multiple limbs are in contact with the ground at any time. Since the animal’s mass is moved by multiple simultaneous ground contacts, it is important to compare GFRs from the same gait cycle, which was not assessed in this study. Moreover, there are several forms of lameness that are not subjectively detected at a trotting speed, while the stance phase is much longer, with greater range of motion of the joints, so the dog tends to show more SI differences when an area of cartilage defect is under strain only during walking.

Subject velocity has a significant effect on the FP values and must be limited to a narrow range when data are obtained. It was reported that a change in velocity of 0.6 m/s or more affected PVFs of the hindlimbs during trot. During the present study, changes in velocity did not have an effect on PVF because all velocity ranges were within 0.6 m/s. The range of 1.3 to 1.5 m/s was excluded when setting the gait velocity because it represents a range of velocity that could be either walk or trot, depending.
on the dog. It is also important to consider whether the animal is accelerating or decelerating,\textsuperscript{27} which creates a turning moment around the center of mass that changes the relationship between the front and hind vertical forces.\textsuperscript{26}

As the gait velocity increased, the PVF increased and VI decreased in the forelimbs and hindlimbs. The results were in accordance with the prediction that at higher speeds contact time decreases, so that impulse must be provided with higher peak force; therefore, as a stepping force, the force in the Fz direction must increase with increasing velocity, since the animal must support its body weight against gravity; thus, vertical force must increase so that the average vertical force over the stride matches the weight of the animal. These results are similar to those of previous studies.\textsuperscript{10,13,14} This may also be true because the stance time shortens as the velocity increases; therefore, VI, the area enclosed by time and force curves, decreases, and the instantaneous force, or PVF, increases.\textsuperscript{12,18} Comparisons of the forelimbs and hindlimbs showed them to be loaded at approximately 60% and 40%, respectively, at all velocities, which was consistent with previous reports.\textsuperscript{13-15} This may be because the forelimb is more likely to be loaded than the hindlimb because of the weight of the head and the amount of muscle mass in the forebody; in other words, the animal’s center of mass is closer to the forelimbs than to the hindlimbs. At all velocities, the PBF and BI were significantly higher than the PPF and PI in the forelimbs; however, the opposite was observed in the hindlimbs. This suggests that the hindlimbs are mainly responsible for propulsive force and the forelimbs are mainly responsible for suppressive force, consistent with a previous report.\textsuperscript{16,26} This explains why the hip retractors are substantially more massive than the protractors, suggesting a greater capacity for acceleration from the hindlimb, although the shoulder has a more equal distribution of retractor and protractor muscle mass with no obvious predominance of protractors.\textsuperscript{26}

As the velocity increased, the PPF significantly increased in the forelimbs; this tendency was also observed in the hindlimbs. This instantaneous increase in the PPF was considered attributable to the shortening of the stance time and PVF.\textsuperscript{13} This increase in the PPF is predictable because at higher speeds contact time decreases, so that impulse must be provided with higher peak force. The force in the craniocaudal direction should be constant under constant velocity, as in the present study. The increase in PPF with increasing velocity is thought to be due to the fact that the increase in PPF of one limb is balanced by the force in the craniocaudal direction in the whole animal. However, there was no difference among PIs at all velocities. In previous studies of Greyhounds, the PI tended to decrease with increasing velocity; however, this was not consistent with the results of the present study. The PI is calculated by multiplying the propulsive directional force and stance time. It has been suggested that the stance time decreases when the gait velocity increases. This could be because, while the standing time is reduced, the propulsive directional force increased more for Beagles, with shorter limbs compared with Greyhounds, because the dogs walked at the same velocities, which required faster limb movement in the smaller breed.\textsuperscript{11} It was suggested that this tendency would be a feature of small-sized dogs.

As the velocity increased, the PBF significantly increased in the forelimbs and hindlimbs, due to the fact that limb contact is made at higher velocity and larger limb angle, leading to a larger contact collision at higher velocity. These results are similar to those of previous studies.\textsuperscript{10,13,14} However, in the present study, no significant difference in the forelimbs during trot 1 and trot 2 was observed. The aforementioned previous studies evaluated Greyhounds. It has been suggested that Beagles, which have a smaller physique and need to move their limbs faster to attain the same velocity,\textsuperscript{4,5} would not attain the velocity of trot 2 when the forelimbs are suppressed. In contrast, there was no difference among BIs at all velocities. Previous studies of Greyhounds reported that the BI tended to decrease with increasing velocity; however, this was not consistent with the present results. It was suspected that the reason for the discrepancy in results of the BI was the same as that for the discrepancy in results of the PI.

There was no significant difference among all parameters in the Fx direction at all velocities, which was consistent with previous reports.\textsuperscript{10} The PLF was significantly higher than PMF in the forelimbs during trot 1 and trot 2; however, there was no significant difference between the PLF and PMF in the hindlimbs at all velocities. In other words, weight bearing at the grounding site of the forelimbs was significantly more lateral than medial. This is because the forelimb is mainly responsible for the PBF and BI, which are suppressive forces, and the force is applied in the lateral direction, which is the stable direction. As previous studies did not show a definite trend in GRFs in the Fx direction, this trend could be a new finding.

A limitation of this study was that we considered absolute velocity rather than relative velocity, which accounts for the physique. Bertram et al\textsuperscript{19} compared gaits of Labrador Retrievers and Greyhounds using functional limb length, body weight, and relative velocity to normalize the data.\textsuperscript{19} Differences between breeds were mainly attributed to differences in body size, and the dogs moved in a dynamically similar manner. Moreover, some studies\textsuperscript{9} that included GRF data of dogs have provided descriptions of the habituation of dogs to the gait analysis laboratory or data-gathering routine. It is possible that the habituation time of the Beagles included in this study was insufficient; therefore, excessive repetition of walking trials would have led to variations. Eighteen Beagles were included in this study, but that number was insufficient; however, the number of animals was comparable to that of previous studies. As we did not have control over stride length, we tried to keep the velocity of linear motion as constant as possible by strictly controlling the acceleration during GRF.
measurements. Any acceleration causes a turning moment around the center of mass that redistributes the vertical force between fore and hindlimb,\(^{26}\) which was not considered in this study, in which the GRF occurring in each limb at the same time was not measured.

In summary, the results of the GRF analysis used in the present study may be useful for comparing healthy Beagles with those with diseases when pre-morbid data are not available. Because the forelimbs are mainly responsible for the suppressive force, it is suggested that weight bearing is more stable in the forelimbs than in the hindlimbs, which are mainly responsible for propulsive force, and that a greater force is generated laterally than medially.

**Acknowledgments**

The funding sources did not have any involvement in the study design, data analysis and interpretation, or writing and publication of the manuscript.

The authors declare that there were no conflicts of interest.

We thank Editage (www.editage.com) for English language editing. We also thank the students of the Laboratory of Small Animal Surgery, Azabu University, and Vetz Petz for their support.

**References**


**Supplementary Materials**

Supplementary materials are posted online at the journal website: avmajournals.avma.org