Comparison of temporospatial and kinetic variables of walking in small and large dogs on a pressure-sensing walkway

Jongmin Kim, DVM, PhD; Kris A. Kazmierczak, BS; Gert J. Breur, DVM, PhD

**Objective**—To compare temporospatial variables (TSVs) and kinetic variables (KVs) for forelimbs and hind limbs of small and large dogs of various breeds during walking and to determine associations among body weight (BW), TSVs, and KVs in these groups. **Animals**—12 adult dogs with no evidence of lameness. **Procedures**—Dogs (grouped according to BW as small (< 10 kg; n = 6) or large (> 25 kg; 6)) were walked in a straight line at their preferred velocity on a wooden platform with an embedded pressure-sensing walkway. Five valid trials were analyzed for each dog; mean TSVs and KVs were determined for each group. The TSVs and KVs for forelimbs and hind limbs were compared between groups, and correlations among BW, TSVs, and KVs were determined. **Results**—Small dogs had significantly smaller TSVs and KVs than did large dogs. Temporal variables of small dogs and absolute vertical force variables of small and large dogs increased as BW increased. However, normalized peak vertical force and weight distribution values among the 4 limbs were similar between groups. **Conclusions and Clinical Relevance**—Substantial similarities and differences were detected in gait characteristics between small and large dogs. Results indicated TSVs and KVs can be used for comparison of the walking gait between dogs or for comparison of variables between limbs in an individual dog. Use of the pressure-sensing walkway is a simple method for acquisition of TSVs and KVs for large and small dogs. (Am J Vet Res 2011;72:1171–1177)
as for large dogs and whether the relationship can be
generalized to the entire dog population.

Most studies on canine gait have been conducted
in large-breed dogs. It is unknown whether normal gait
in small dogs has the same characteristics as in large
dogs. It is also not known whether gait in small dogs
can be evaluated by use of techniques similar to those
used in large dogs. These lingering questions prohibit
more widespread use of gait analysis in dogs, and these
questions must be addressed before gait analysis can be
used as a routine diagnostic tool in clinical orthopedics
or as a functional outcome measure in clinical studies
that include dogs of all sizes. The purpose of the study
reported here was to compare TSVs (including gait
velocity, durations of the gait cycle, stance phase, and
swing phase; duty factor, cadence, and PCA) and KVs
(including PVF, MVF, VI, FCP, and weight distribution)
of the forelimbs and hind limbs of small and large dogs
during walking and to assess the utility of PSWs for de-
termination of these variables for small and large dogs.

We hypothesized that small dogs would have different
TSVs and different kinetic gait patterns during walking
than large dogs and that BW would be associated with
the magnitude of TSVs and KVs.

Materials and Methods

Animals—Two groups of 6 adult dogs were includ-
ed in the study. All dogs were determined to be free
of lameness by means of a physical examination by a
veterinarian. The small-dog group consisted of dogs <
10 kg (mean BW, 5.8 kg [range, 2.6 to 8.7 kg]); 2 Jack
Russell Terriers, 1 Chihuahua, 1 Cavalier King Charles
Spaniel, 1 miniature Poodle, and 1 mixed-breed dog),
and the large-dog group included dogs > 25 kg (mean
BW, 37.3 kg [29.1 to 44.7 kg]; 3 Labrador Retrievers, 2
Golden Retrievers, and 1 Boxer). All dogs were owned
by veterinary students or staff of the veterinary teach-
ing hospital. Written owner consent was obtained be-
fore the study. The study was approved by the Purdue
Animal Care and Use Committee.

Data acquisition—Dogs were walked on a leash,
al by the same handler, in a straight line, on a PSW
eMBEDDED IN A 9-M WOODEN WALKWAY. Each dog was al-
lowed to walk at its preferred velocity. Nine photocells
positioned 0.5 m apart along the side of the platform
were coupled with a triggered timer system and were
used to estimate gait velocity. The PSW (0.5 m wide
and 2.0 m long) consisted of a grid of sensors (3.9 sen-
sors/cm²) embedded in a plastic mat. The PSW was cal-
librated according to the manufacturer’s specifications
and recorded walking variables at a 60-Hz sampling
frequency. A digital video camera was positioned 3.5 m
from the center of the platform on the side opposite
from the photocells to record limb motion at the PSW.
The data obtained from the PSW were analyzed by use
of designated software.b

Before data acquisition, each dog was weighed
on an electronic scale and walked across the walkway
3 to 5 times to allow it to become accustomed to the
PSW, handler, and leash. At least 10 trials were record-
ed for each dog, and data from the first 5 valid trials
were analyzed. A valid trial included a straightforward
walk without stopping, hesitating, trotting, or pacing;
no overt head movement during the trial; and mainte-
nance of a constant speed on the PSW within the velocity
and acceleration ranges (0.5 to 1.5 m/s and –1.0 to
1.0 m/s², respectively).

Data processing—Each frame of the video record-
ing of a trial was reviewed by 1 investigator (JK) to
analyze the sequence of placement for all 4 limbs on
the PSW and the corresponding frame numbers of each
paw print. After identification of the sequence of paw
placement on the PSW, stride length was measured as
the distance in millimeters from the most caudal pixel
of the first contact of the paw on the PSW to the most
caudal pixel of the next contact of the same paw. This
was repeated for every complete stride recorded on the
PSW and for all 4 limbs, and values were later convert-
ed to meters. All paw prints displayed at peak mode on
the PSW were marked by use of the box tool included
in the software package, and GRF and paw contact area
data for each limb were saved frame by frame in an
American Standard Code for Information Interchange
(ASCII) file and transferred to a spreadsheet program.c

Gait cycle duration, measured in seconds, was de-
cined as the interval between the first frame of the first
step of one paw on the PSW and the first frame of the
next consecutive step of the same paw and was calcu-
lated by dividing the numbers of frames per gait cycle
by the sampling rate (60 Hz). A gait cycle of each limb
was considered complete if the stance phase and the
following swing phase were identified on the PSW and
on the corresponding video recording. Stance phase du-
nation (s) of each limb was calculated by dividing the
number of frames that displayed any force data for a
limb by the sampling rate (60 Hz). The stance phase
duration was also represented as fraction of the gait
cycle duration (duty factor = stance phase duration/gait
cycle duration).11 The swing phase duration (s) was cal-
culated as the stance phase duration subtracted from
the gait cycle duration. The LV (m/s) of each complete
stride was calculated as the stride length divided by the
frame per gait cycle duration. The mean gait velocity
of a dog was defined as the mean velocity of the 8
velocity measurements/trial recorded via the photocells
and designated software.4 The cadence of forelimbs
and hind limbs of a dog was calculated by use of the follow-
ing equation:

For nonlimb (or hind limb) cadence (steps/min) =
(total number of forepaw [or hind paw] strikes on the
PSW X 60)/time between the first frame of the first fore-
paw [or hind paw] strike and the last frame of the last
forepaw [or hind paw] strike on the PSW (s).

Measurement of TSVs was performed for limbs
with complete gait cycles recorded on the PSW. Depend-
ing on the location of the first step on the PSW, 1 or 2
gait cycles/limb/trial were evaluated for dogs included
in the large-dog group and 5 or 6 gait cycles/limb/trial
were evaluated for dogs in the small-dog group.

Vertical GRF data acquired via PSW were saved as
an ASCII file and transferred to a spreadsheet. The PVF
(N), defined as the greatest vertical force measured dur-
ing the stance phase; the MVF (N), defined as the mean
of vertical force values during the stance phase; and the
VI (N × s), defined as the sum of vertical forces during the stance phase, were recorded for each paw placement on the PSW. For purposes of comparison, PVF, MVF, and VI of each limb were normalized to the dog’s BW and represented as a percentage of BW and as percentage of BW × s. The PVF was also used to calculate the percentage of BW distribution among the 4 limbs by use of the following equation:10

\[ \text{Distribution of BW (\%)} = \frac{\text{PVF of the limb}}{\text{total PVF of all 4 limbs in 1 gait cycle}} \times 100. \]

Paw contact area and paw pressure measurements obtained with the PSW during each stance phase were also saved as an ASCII file. Values were transferred to a spreadsheet and used to define the PCA (cm²) and PCP (kPa) of each paw strike during walking.

The SI between left and right limbs was expressed as a percentage of the difference between the 2 limbs relative to the mean of the 2 limbs for the same gait variable. The SI was calculated for each TSV and KV by use of the following equation:12:

\[ \text{SI (\%)} = \frac{(|X_r - X_l| - 0.5|X_r + X_l|)}{X_r} \times 100 \]

where \( X_r \) is the value for the variable of interest of the right limb and \( X_l \) is the same value for the left limb.

**Statistical analysis**—Mean ± SD (range) of the following variables were determined for forelimbs and hind limbs of each dog: gait velocity, gait cycle duration, stance phase duration, swing phase duration, duty factor, stride length, LV, PVF, MVF, VI, PCA, PCP, BW distribution among 4 limbs, and SI. Each of the TSVs and KVs were compared by use of an independent sample \( t \) test to detect significant differences between groups. *Values differ significantly (\( P < 0.05 \)) between forelimb and hind limb.

**Results**

Mean values of all TSVs measured in small dogs were significantly different from those measured in large dogs (Table 1). Duty factors of all dogs in the present study were > 0.50, which indicated that all dogs were walking during data acquisition. However, mean duty factors of the forelimbs (0.38 ± 0.04) and hind limbs (0.55 ± 0.04) of small dogs were significantly smaller than those of large dogs (0.64 ± 0.02 and 0.62 ± 0.02 in forelimbs and hind limbs, respectively). Mean durations of gait cycle, stance phase, and swing phase of the walk were significantly shorter, and mean gait and limb velocities were significantly lower, in small dogs than in large dogs. Mean gait cadence was significantly higher in small dogs, compared with that in large dogs.

Mean swing phase duration was significantly longer in the hind limbs than in the forelimbs of dogs in both groups. In small dogs, because the stance phase duration of the hind limb was significantly shorter than that of the forelimb, mean gait cycle duration was not different between forelimbs and hind limbs. In large dogs, mean gait cycle duration of the hind limb was longer than that of the forelimb, and mean stance phase duration was significantly longer than that in small dogs. No significant differences were detected between mean TSVs of the left and right forelimb or left and right hind limb in either group. No significant differences were detected between mean SIs of forelimb and hind limb TSVs or KVs of dogs in either group, and mean SIs for these variables were not significantly different between small and large dogs (Table 2).

Mean values of nonnormalized PVFs, MVFs, and VIs of forelimbs and hind limbs were significantly smaller in the small dogs than in the large dogs. However, after normalization for BW, mean PVFs of the forelimbs (43.10 ± 5.15% of BW) and hind limbs (27.83 ± 3.02% of BW) of small dogs were not significantly different from those of large dogs (43.26 ± 2.54% of BW for forelimbs and 26.89 ± 1.83% of BW for hind limbs) as a percentage of BW (range, 0.98 to 1.07 m/s).

Table 1—Mean ± SD (range) TSVs for small (n = 6; gait velocity, 0.76 ± 0.08 m/s [range, 0.68 to 0.88 m/s]) and large dogs (6; gait velocity, 1.02 ± 0.03 m/s [range, 0.96 to 1.07 m/s]).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Small dogs</th>
<th>Large dogs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forelimb</td>
<td>Hind limb</td>
<td>Forelimb</td>
</tr>
<tr>
<td>LV (m/s)</td>
<td>0.72 ± 0.09 (0.61–0.87)*</td>
<td>0.73 ± 0.09 (0.63–0.90)*</td>
</tr>
<tr>
<td>Duty factor</td>
<td>0.58 ± 0.04 (0.52–0.61)†</td>
<td>0.55 ± 0.04 (0.51–0.61)†</td>
</tr>
<tr>
<td>Gait cycle duration (s)</td>
<td>0.51 ± 0.07 (0.40–0.60)†</td>
<td>0.51 ± 0.08 (0.38–0.61)†</td>
</tr>
<tr>
<td>Stance phase duration (s)</td>
<td>0.30 ± 0.06 (0.21–0.38)†</td>
<td>0.28 ± 0.06 (0.19–0.38)†</td>
</tr>
<tr>
<td>Swing phase duration (s)</td>
<td>0.21 ± 0.02 (0.18–0.25)†</td>
<td>0.23 ± 0.02 (0.19–0.28)†</td>
</tr>
<tr>
<td>Stride length (m)</td>
<td>0.37 ± 0.06 (0.25–0.49)†</td>
<td>0.37 ± 0.06 (0.25–0.49)†</td>
</tr>
<tr>
<td>PCA (cm²)</td>
<td>7.90 ± 2.37 (5.27–11.33)†</td>
<td>3.59 ± 1.40 (1.68–6.18)†</td>
</tr>
</tbody>
</table>

Twelve nonlame adult dogs of various breeds were assigned to small- and large-dog groups according to BW (< 10 kg and > 25 kg, respectively). Dogs were walked on a wooden platform with an embedded PSW, and 5 valid trials were analyzed for each dog; mean TSVs were determined for each group. Gait velocity was significantly different between groups. *Values differ significantly (\( P < 0.05 \)) between groups. †Within a group, values differ significantly between forelimb and hind limb.
limbs; Figure 1; Table 3). Mean values of MVFs and VIs normalized to BW remained significantly smaller in small dogs than in large dogs, and mean PCA and PCP of paws of the forelimbs and hind limbs during the stance phase were also significantly smaller in small dogs, compared with those of large dogs. Mean weight distribution between forelimbs (mean value for both forelimbs, 60.68% of BW) and hind limbs (mean value for both hind limbs, 39.32%) of small dogs was not significantly different from that (61.66% and 38.34%, respectively) of large dogs. The KVs of forelimbs were all significantly greater than those of hind

Table 2—Mean ± SD (range) SIs (%) for TSVs and KVs of the 12 dogs in Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Small dogs</th>
<th>Large dogs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forelimb</td>
<td>Hind limb</td>
</tr>
<tr>
<td>LV</td>
<td>0.95 (0.00–3.23)**</td>
<td>1.36 (0.00–3.97)**</td>
</tr>
<tr>
<td>Gait cycle duration</td>
<td>1.36 (0.00–2.47)</td>
<td>1.13 (0.00–4.17)</td>
</tr>
<tr>
<td>Stance phase duration</td>
<td>4.02 (0.00–9.23)</td>
<td>3.19 (0.00–7.14)</td>
</tr>
<tr>
<td>Duty factor</td>
<td>4.54 (1.07–6.36)</td>
<td>3.76 (0.24–6.39)</td>
</tr>
<tr>
<td>PCA</td>
<td>4.96 (1.50–9.52)</td>
<td>4.43 (0.28–10.33)</td>
</tr>
<tr>
<td>PVF (% BW)</td>
<td>43.10 ± 5.15 (36.97–51.81)**</td>
<td>27.83 ± 3.02 (21.44–32.21)**</td>
</tr>
<tr>
<td>MVF (N)</td>
<td>5.35 ± 2.51 (1.78–9.71)**</td>
<td>3.18 ± 1.70 (0.88–4.63)**</td>
</tr>
<tr>
<td>MVF (% BW)</td>
<td>9.51 ± 1.48 (6.92–11.38)**</td>
<td>5.52 ± 0.96 (4.36–7.42)**</td>
</tr>
<tr>
<td>VI (N x s)</td>
<td>1.73 ± 1.04 (0.39–3.68)**</td>
<td>0.99 ± 0.69 (0.17–2.34)**</td>
</tr>
<tr>
<td>VI (% BW x s)</td>
<td>2.77 ± 0.93 (1.53–4.31)**</td>
<td>1.54 ± 0.63 (0.66–2.75)**</td>
</tr>
<tr>
<td>PCP (KPa)</td>
<td>44.88 ± 12.68 (30.20–69.20)**</td>
<td>35.75 ± 9.35 (13.24–49.00)**</td>
</tr>
<tr>
<td>Weight distribution (% BW)</td>
<td>30.34 ± 6.00 (26.41–33.75)**</td>
<td>19.66 ± 0.52 (16.28–22.84)**</td>
</tr>
</tbody>
</table>

The SI between left and right limbs was expressed as a percentage of the difference between the 2 limbs relative to the mean of the 2 limbs for the same gait variable. Values are not significantly different between groups or between forelimbs and hind limbs within a group.

Figure 1—Representative PSW recordings of PCP and the corresponding force-time curves generated from GRF data normalized to BW from a small dog (A) and a large dog (B). Dogs were grouped according to BW (small, <10 kg; large, >25 kg). Larger paw prints represent the forepaws, and smaller paw prints represent the hind paws in each image, with direction of walking from left to right. Pressure was color coded as follows: dark blue, light blue, green, yellow, orange, and red, where dark blue represents the lowest value range (0.00 to 3.85 kPa in a small dog and 0.00 to 11.54 kPa in a large dog) and red represents the highest value range (46.15 to 50.00 kPa in a small dog and 138.46 to 150.00 kPa in a large dog). Higher force curves represent vertical GRFs of the forelimbs and lower force curves represent vertical GRFs of the hind limbs in each force-time curve.

Table 3—Mean ± SD (range) KVs of the 12 dogs in Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Small dogs</th>
<th>Large dogs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forelimb</td>
<td>Hind limb</td>
</tr>
<tr>
<td>PVF (% BW)</td>
<td>43.10 ± 5.15 (36.97–51.81)**</td>
<td>27.83 ± 3.02 (21.44–32.21)**</td>
</tr>
<tr>
<td>MVF (N)</td>
<td>5.35 ± 2.51 (1.78–9.71)**</td>
<td>3.18 ± 1.70 (0.88–4.63)**</td>
</tr>
<tr>
<td>MVF (% BW)</td>
<td>9.51 ± 1.48 (6.92–11.38)**</td>
<td>5.52 ± 0.96 (4.36–7.42)**</td>
</tr>
<tr>
<td>VI (N x s)</td>
<td>1.73 ± 1.04 (0.39–3.68)**</td>
<td>0.99 ± 0.69 (0.17–2.34)**</td>
</tr>
<tr>
<td>VI (% BW x s)</td>
<td>2.77 ± 0.93 (1.53–4.31)**</td>
<td>1.54 ± 0.63 (0.66–2.75)**</td>
</tr>
<tr>
<td>PCP (KPa)</td>
<td>44.88 ± 12.68 (30.20–69.20)**</td>
<td>35.75 ± 9.35 (13.24–49.00)**</td>
</tr>
</tbody>
</table>

Data for KVs were examined as recorded and as values normalized to BW where indicated. See Table 1 for key.
limbs in small and large dogs. There was no significant difference between contralateral forelimb or hind limb KVs in either group, and there were no significant differences in SIs of KVs between forelimbs and hind limbs or between small and large dogs (Table 2).

Mean TSVs and KVs, except for VI and PCP, of all dogs had CVs < 10% (Table 4). The highest CVs for small and large dogs were detected for PCP. The CVs of forelimb VI and hind limb PCA of small dogs were significantly greater than those of large dogs. In small dogs, there were significant differences between forelimb and hind limb CVs of gait cycle duration, stance phase duration, VI, and weight distribution. In large dogs, there were significant differences between forelimb and hind limb CVs of MVF, PCA, and weight distribution.

There was a significant correlation between BW and nonnormalized KVs, except for PCP, in dogs of both groups. The BW was significantly correlated with PCA in dogs of both groups, except for forelimb PCA in large dogs (P = 0.053). In small dogs, there was also significant positive correlation between BW and the TSVs of gait cycle duration, stance phase duration, and swing phase duration. In large dogs, the correlation between BW and TSVs did not reach significance, except for PCA of the hind limb. The KVs normalized to BW were negatively correlated with BW in the large dogs, but this was only significant for normalized PVF. In general, if there was a significant correlation between BW and a variable of the forelimb, a similar correlation was detected for the hind limb (Table 5).

Discussion

Data of the present study suggest that during a walk at each dogs’ preferred pace, small dogs had more frequent paw strikes and a shorter gait cycle, compared with those of large dogs. These results supported our hypotheses: most TSVs and KVs of small dogs were significantly smaller than those of large dogs, and for many variables, these values increased within group as BW increased. However, weight distribution among the 4 limbs and PVFs normalized for BW were not different between small and large dogs in the study reported here. Use of the PSW was a simple means to acquire both TSVs and KVs for dogs in either size group.

As expected, all TSVs of walking in small dogs were smaller than those in large dogs. The force-driven harmonic oscillator model has been used to predict the duration of the gait cycle of the walking and running of quadrupeds and walking of humans. Gait cycle duration is estimated by the walking cycle period by use of the following equation:

$$\text{Walking cycle period} = 2\pi \sqrt{L/2g}$$

where g is the gravitational constant (9.8 m/s²) and L is the pendulum length (ie, length of the limb of interest). In this calculation, a limb is evaluated as a simple pendulum of negligible mass without any consideration of the active and passive structures within a limb during swing phase. According to the described equation with the assumption that a limb is without any active or passive control, swing phase duration increases logarithmically as limb length increases. This may partially explain the differences detected in durations of swing phase and gait cycle between small and large dogs in the present study.

All KVs of walking were smaller in small dogs than in large dogs, except for PVF normalized to BW and percentage of BW distribution for forelimbs and hind limbs. In addition, nonnormalized KVs except for PCP increased within a group as BW increased. These findings are consistent with Newton’s second law, which states that force is a function of mass. We also detected a negative correlation between normalized PVF and BW in large dogs but not in small dogs. A negative correlation between these variables was previously reported in a study of 17 dogs during walking on a force plate; mean (range) BW of the dogs in that study was 26 kg (8.6 to 58.5 kg), and only 2 dogs < 10 kg were included. In addition to the fact that the previous study involved mostly large dogs, the measurement system in the study reported here was different from that of the previous study. The results of the present study suggest that a negative correlation between normalized PVF and BW may not be generalized to all dogs. Further investigation including a larger population of dogs of

Table 4—Mean (range) CV (%) of TSVs and KVs of the same small (n = 6; CV of gait velocity, 3.95% [range, 1.13% to 6.76%]) and large (6; CV of gait velocity, 4.81% [range, 3.50% to 6.50%]) dogs in Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Small dogs</th>
<th>Large dogs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forelimb</td>
<td>Hind limb</td>
</tr>
<tr>
<td></td>
<td>Forelimb</td>
<td>Hind limb</td>
</tr>
<tr>
<td>LV</td>
<td>7.60 (4.40–11.19)</td>
<td>7.71 (4.96–12.30)</td>
</tr>
<tr>
<td></td>
<td>5.23 (4.36–6.08)</td>
<td>5.42 (4.423–7.03)</td>
</tr>
<tr>
<td>Gait cycle duration</td>
<td>6.40 (2.02–14.35)</td>
<td>5.24 (1.38–12.40)</td>
</tr>
<tr>
<td></td>
<td>4.07 (2.04–6.94)</td>
<td>3.82 (2.52–5.10)</td>
</tr>
<tr>
<td>Stance phase duration</td>
<td>7.18 (2.29–16.93)</td>
<td>5.34 (1.38–12.40)</td>
</tr>
<tr>
<td></td>
<td>4.37 (2.53–6.61)</td>
<td>5.20 (3.37–7.74)</td>
</tr>
<tr>
<td>Duty factor</td>
<td>2.20 (0.80–4.06)</td>
<td>2.63 (1.38–4.50)</td>
</tr>
<tr>
<td></td>
<td>1.82 (0.89–4.17)</td>
<td>2.10 (1.14–4.17)</td>
</tr>
<tr>
<td>Gait cadence</td>
<td>4.90 (2.16–8.05)</td>
<td>4.58 (2.16–7.77)</td>
</tr>
<tr>
<td></td>
<td>9.37 (8.31–11.23)</td>
<td>10.66 (8.56–14.31)</td>
</tr>
<tr>
<td>PCA</td>
<td>4.92 (1.18–9.23)</td>
<td>4.72 (2.92–6.11)</td>
</tr>
<tr>
<td></td>
<td>2.73 (0.74–4.43)</td>
<td>3.23 (2.82–3.83)</td>
</tr>
<tr>
<td>PVF</td>
<td>4.50 (1.71–8.43)</td>
<td>4.72 (2.92–6.11)</td>
</tr>
<tr>
<td></td>
<td>3.13 (2.19–4.65)</td>
<td>4.08 (2.42–5.66)</td>
</tr>
<tr>
<td>MVF</td>
<td>8.79 (0.56–14.98)</td>
<td>7.48 (3.16–14.09)</td>
</tr>
<tr>
<td></td>
<td>5.36 (3.11–11.29)</td>
<td>6.45 (1.85–15.14)</td>
</tr>
<tr>
<td>VI</td>
<td>15.54 (2.42–27.84)</td>
<td>12.66 (4.64–24.13)</td>
</tr>
<tr>
<td></td>
<td>8.23 (2.62–15.30)</td>
<td>7.90 (6.06–15.76)</td>
</tr>
<tr>
<td>PCP</td>
<td>18.08 (9.68–27.70)</td>
<td>15.79 (11.64–26.18)</td>
</tr>
<tr>
<td>Weight distribution</td>
<td>2.69 (1.75–3.86)</td>
<td>4.16 (3.04–5.63)</td>
</tr>
<tr>
<td></td>
<td>1.99 (0.89–2.88)</td>
<td>3.18 (1.44–4.54)</td>
</tr>
</tbody>
</table>

See Table 1 for key.
variouss sizes is warranted to determine the definitive relationship between PVF and BW during walking.

The most commonly used KVs of limb function are PVF and VI.5,6 However, PVF is a single point value during a stance phase and VI is significantly affected by the duration of a stance phase. We included nonnormalized and normalized MVFs in the present study because MVF determined from measurements of vertical forces of a limb during stance phase, may be a variable that incorporates the magnitude and duration of the vertical force simultaneously. In the study reported here, non-normalized MVFs of small and large dogs were significantly correlated with BW, as were nonnormalized PVFs and VIs. In the present study, the PCP of paws during stance phase was introduced to represent PVF normalized to paw size to compare VFs of different paw sizes. Even though PCA was significantly correlated with BW in the forelimbs and hind limbs of small dogs and in the hind limbs of large dogs, PCP in each group of dogs was not correlated with BW in the present study. It may be that the high interdog variability of PCPs (evidenced as high mean CVs) in small and large dogs in the present study masked a relationship between these variables.

Findings of the present study suggest that gait variables assessed by use of a PSW can be compared between dogs and also between the limbs of an individual dog at a walk. For example, BW distribution among the 4 limbs was not affected by BW or size group of dogs in the present study. This suggests that BW distribution among limbs may be a useful variable to determine gait differences between walking dogs, regardless of their size. Thus, it may be possible to establish a reference range for BW distribution among forelimbs and hind limbs in healthy dogs. Other KVs were significantly correlated with BW in the present study, and it may be feasible to establish their reference values as a function of BW. In contrast, other variables, including TSVs, appear to be more suitable to determine differences between left and right limbs, or fore- and hind limbs in an individual dog. To facilitate clinical gait analysis, it is essential to have established reference ranges for these values. Reference ranges may be affected not only by the intrinsic variability of gait and conformation of an individual dog but also by breed differences. Therefore, further studies should include analysis of a large population of dogs of different sizes, shapes, and breeds.

In the study reported here, SIs of TSVs and KVs were included as reference values. Symmetry is often assumed to be a characteristic feature of normal gait, and measurements of gait symmetry are often used as indicators of gait dysfunction, as diagnostic tools, or as a means of monitoring treatment responses in humans.14 In dogs, the SI of PVF in hind limbs has been used to detect mild hind limb lameness during walk and trot.15 However, asymmetric joint moment during a trot has been reported in a normal dog.16 Therefore, which variables best express gait symmetry and how much asymmetry may be considered normal remain under debate.

In the present study, CV was used as a measure of precision and repeatability of the 5 valid trials used for data analysis. Many factors, such as gait velocity, acceleration, or stride length, may increase the CV and therefore should be carefully controlled during data acquisition. Recently, it was reported that a large CV of TSVs may be associated with ataxia.5,6 Some variables, such as VI and PCP, appeared to have inherently large CVs in the present study and therefore may be less useful for routine gait analysis.

The PSW and related equipment used in the present study detected and recorded vertical GRF, dynamic paw pressures, and TSVs in small and large dogs. Although it was evident that multiple paw strikes of dogs in both groups overlapped at the preferred walking pace, analysis of TSVs and KVs of a given paw strike was not affected by other paw strikes on the PSW. The PSW used was 2 m long, which allowed small dogs ≥ 4 strides (8 paw strikes) of any limb and large dogs 1 complete stride of all 4 limbs during a single trial on the walkway. Therefore, with this PSW, it may be possible that as many as 3 paw strikes of the same limb may be acquired in a single gait trial for small dogs, which would be beneficial for those that cannot perform multiple trials because of abnormal limb function or uncooperative behavior. In addition, it is possible to identify and analyze BW distribution among all 4 limbs during a single gait trial on the PSW. With a force plate, at least 2 trials are required to acquire the GRF of 4 limbs, and if the 2 trials are not identical, the calculated BW distribution may be different from the actual value.

To compare gait variables among different animals or different groups, all animals should be moving at a similar velocity because gait velocity will affect TSVs and KVs.17–19 However, it may be impossible for small dogs or lame dogs to generate the same walking velocity generated by the large dogs or nonlame dogs, respectively, because of differences in body dimensions or limb function. Therefore, in the present study, we used the duty factor (ie, fraction of stance phase during gait cycle [stance phase + swing phase]) to determine whether a dog was walking. During walking, stance phase is longer than swing phase (duty factor > 0.5).11 As walking velocity increases, the absolute and relative stance phase shortens, and when swing phase exceeds stance phase, the walk has changed to a run (trot or pace, duty factor < 0.5).11 In the present study, all dogs in both groups had duty factors > 0.5, and thus were considered to be walking during the gait trials, even though the mean duty factor for small dogs was significantly smaller than that for large dogs. It is possible that small dogs walked faster, relative to large dogs, to match the handler’s gait because of the greater discrepancy in body dimension between small dogs and the handler. However, the relatively fast and slow walking gaits may be natural to small and large dogs, respectively, because all dogs walked ahead of the handler when triggering photocells in the present study.

Limitations of the present study include the lack of medium-sized (10- to 25-kg) dogs and the small number of dogs in each group. Because linear correlation is sensitive to outliers in data, the overall correlation for data from the 2 distinct groups in the present may have been misleading if we simply pooled results for dogs in each group. We did not report pooled data of small and large dogs because of the 2 distinct groups of dogs in the present study: Inclusion of medium-sized dogs in
the present study may possibly have resulted in more definitive correlations between gait variables and BW. Differences in many variables between small and large dogs were notable, even with the small number of dogs in each group. However, increased numbers of dogs might have reduced the variability of data and might have enhanced the determination of characteristics for each group.

To the authors’ knowledge, the study reported here is the first to describe TSVs and KVs of walking in small dogs and to compare variables of this gait between small and large dogs and between forelimbs and hind limbs. The results indicated significant similarities and differences in the walking gait between small and large dogs that may enhance our understanding of gait as required for clinical gait analysis in dogs. The TSVs and KVs of small, nonlame dogs obtained with a PSW during walking in the present study may serve as a future reference for evaluation of small dogs with abnormal limb functions. Further research on use of the PSW is justified to determine the relationships among TSVs, KVs, and BW of a larger population of dogs with a more random weight and shape distribution.

References