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Alterations in the ground reaction force of dogs during trot after immobilization of the stifle joint: An experimental study

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ABSTRACT. This study aimed to evaluate changes in the vertical and fore-aft force generation of the hindlimbs in dogs with stifle orthoses. Custom-made orthoses were used on the right stifle joint. Force plate and marker data from four beagle dogs in trials without orthoses, with fixed orthoses, and with unfixed orthoses were collected. The vertical ground reaction force of the right side was increased with fixed orthoses and decreased with unfixed orthoses compared to that of gait without orthoses. When compared to that of gait without orthoses, the fore-aft ground reaction force changed with fixed orthoses but not with unfixed orthoses. It is suggested that the level of constraint of the orthosis affected the ground reaction force pattern.

KEY WORDS: canine stifle joint, gait analysis, orthosis

Previous studies have evaluated human gait following the simulation of knee immobilization by the application of an orthosis or cast [4, 9, 15]. In a comparable study of dogs, carpal motion was restricted by taping, and kinematic gait analysis revealed that the movements of the ipsilateral shoulder and contralateral stifle changed after carpal taping [5]. Another study compared the kinematic data of dogs' hindlimbs with and without stifle orthoses, which are used for cranial cruciate ligament rupture, and found that the range of motion of adjacent joints was affected even though the featured stifle motion was only restricted by a limited amount [16]. To our knowledge, kinetic analyses following the use of orthoses to immobilize the joints of healthy dogs have not been reported.

In this study, we fitted dogs with orthoses to restrict the stifle range of motion and collected the ground reaction force data. The objective of this study was to evaluate the gait alteration after application of the orthoses.

Four beagle dogs (1 male, 3 females) were included in the present study. The median age of the dogs was 2.5 years (2.0–5.4 years), and the median body weight (BW) was 10.25 kg (8.2–11.2 kg). None of the dogs had a history of orthopedic or neural disorders. The dogs were singly housed in separate cages (1.15 m depth, 0.7 m width, 1.75 m height) with 16 hr of light per day. The kennel was kept at 25°C; food was given twice a day, and water was provided *ad libitum*. The animals were allowed to habituate to the experiment room for 1–6 months prior to data collection. All experiments were performed in accordance with our institutional guidelines for care and use of laboratory animals and were approved by the Nippon Veterinary and Life Science University (approval number: 30S-3, 2019K-50).

The orthoses (Toyo Sogu Iryokiguseisakujo, Tokyo, Japan) were originally customized for the hindlimbs of each dog. The stifle apparatus for the right hindlimb was made of a thigh and cnemial component, which were connected by two hinges placed on the medial and lateral sides. The angle of the apparatus could be fixed by locking the hinges with button head screws. The cranial part of the trunk and proximal girth of the contralateral hindlimb were strapped with a soft cloth and attached to the stifle apparatus so that the apparatus would stay in the correct position (Fig. 1). Orthoses were adjusted to each dog through several fittings by an orthotist prior to each experiment.

Normal gait without the orthosis, unfixed gait with the orthosis and without angle limitation, and fixed gait with the orthosis and the stifle angle fixed at 135° were evaluated. The angle of 135° was chosen to mimic the standing posture [14]. The dogs were familiarized walking with the orthosis by spending 30 to 60 min with the orthosis for five days every week for one month (preliminary period). The experiments were conducted in the order of normal gait, fixed gait, and unfixed gait. Normal gait was evaluated before the fitting of the orthosis to avoid the possibility of changes in gait as a result of wearing the orthosis.
A preliminary period was set for each dog prior to both the unfixed and fixed gait assessments, and these gaits were then evaluated and recorded. The fixed and unfixed gait evaluations were separated by at least a one-month preliminary period.

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Dogs were led by one handler and trotted at their favorable speed. Trials were repeated 100 times on one day, and the dogs were allowed to rest for several min after every 20 trials. The ground reaction force was obtained at 960 Hz using two force plates (FPpro-Animal, Hu-tech Co., Ltd, Tokyo, Japan) that were adjacent to each other in the center of a 7 m runway. Each force plate was 30 cm wide and 40 cm long. A trial with only one hindlimb placed at the center of either of the force plates was considered an acceptable trial. The trial was considered unacceptable if more than one limb was simultaneously placed on the same force plate. The force plate data of the hindlimbs were collected using the WAS software (WAS, version 2.31, UNIMEC Co., Ltd., Tokyo, Japan).

Polystyrene markers were used to track movement. Markers were 15 mm in diameter and colored with fluorescent paint. To minimize the effects of fur movement, each marker was attached directly to the skin with a rubber-based solvent-type glue. Markers were placed, on both sides, at the cranial angle of the scapula (SCA), craniodorsal edge of the ilium (ILI), greater tubercle of the femur, lateral femoral epicondyle, and lateral to the styloid process of the fibula. Markers were placed on the skin above the bony landmarks when the dog stood naturally.

Three cameras (FDR-AX40, SONY Corp., Tokyo, Japan) that were 1 m apart were installed on one side of the runway. Videos of each trial were taken at 120 frames per sec. Calibration was performed both statically and dynamically. Static calibration was performed using equipment that had six calibration points located at the center of the force plate. Dynamic calibration was performed using a stick that had two calibration points attached to its end. The calibrated volume of the space was 2 m in length, 1.5 m in width, and 1 m in height. Marker positions were tracked frame-by-frame using the ICpro-3D software (Hu-tech Co., Ltd., Tokyo, Japan). The marker location was validated when the marker was visible in all three cameras; therefore, only one side of the dog was evaluated for marker positions in each trial. Data from the three cameras were combined to obtain the three-dimensional marker position and linked to the force plate data on the ICpro-Analyzer (Hu-tech Co., Ltd.). Data synchronization was performed using 16 LED lights that sequentially turned on and off every msec; the first light turned on when the force plate data collection started. Stance time (ST; sec), peak vertical force (PVF; %BW), peak propulsive force (PPF; %BW), peak braking force (PBF; %BW), vertical impulse (VI; %BW·sec), propulsive impulse (PI; %BW·sec), braking impulse (BI; %BW·sec), trotting velocity, falling distance of ILI (mm), and upward distance of ILI (mm) were evaluated. The PVF, PPF, PBF, VI, PI, and BI were normalized with BW. The craniocaudal velocity of the SCA and ILI was used as the trotting velocity and normalized with the dogs' withers height as described previously [17]. Trials were excluded if the dog's trotting velocity was not in the range of 0.8 to 1.0 or if the velocity changed more than 0.5 m/sec before normalization. Falling distance (mm) was defined as the vertical moving distance of ILI from the highest point immediately before the stance phase to the lowest point during the stance phase. Upward distance (mm) was defined as the moving distance of the same marker from the lowest point during the stance phase to the highest point immediately after the stance phase. Vertical movement of the markers was only evaluated if the limb on the force plate was on the same side as the cameras. The stifle marker position during the assessment of the fixed and unfixed gaits was estimated using the length of the thigh and cnemial segments that had been calculated from the assessment of the normal gait, and the range of motion of the stifle joint was evaluated for the right hindlimb during the assessment of each gait. These values were obtained using the Excel software (Excel 2016, Microsoft Corp., Redmond, WA, USA). Since only one side of the dog was evaluated for marker positions for each trial, the kinetic and kinematic data were observed on the sagittal plane. Data from the right and left sides were taken as separate and used for statistical analysis if there were more than four acceptable trials.

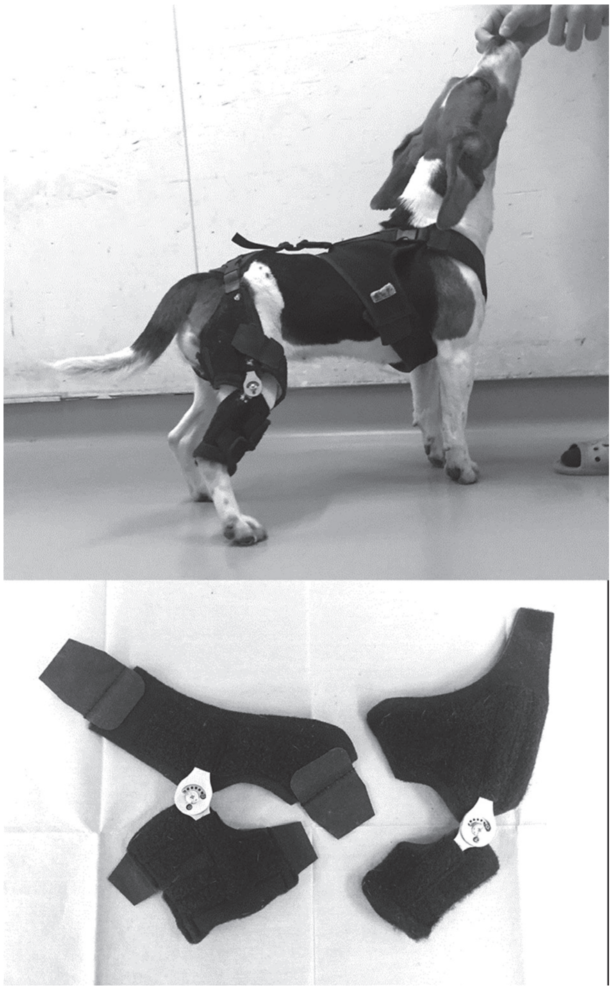

Fig. 1. The orthoses were custom-made for each dog. The cranial part of the trunk and proximal girth of the left hindlimb were strapped with a soft cloth and attached to the right stifle apparatus so that the orthosis would stay in the correct position. The right stifle apparatus had hinges on the medial and lateral sides. The photo on the bottom shows the right stifle apparatus. The medial part is on the left and the lateral part is on the right.

A simple linear regression was performed to evaluate the association between velocity and the three gaits. Although the trial velocity was limited to between 0.8 and 1.0, the velocity of the unfixed gait was significantly lower than that of the normal gait (coefficient. −0.0684, P<0.01), thus, it was included in the multiple regression analysis as an independent variable. A multiple linear regression was performed to evaluate the association between ST, PVF, PPF, PBF, VI, PI, BI, falling distance of the ILI,

Table 1. Median (range) of the ground reaction force and marker movement of the hindlimbs

		Right	Left
ST (sec)	Normal	0.202 (0.192–0.204)	0.198 (0.184–0.204)
	Unfixed	0.217 (0.207–0.246)	0.214 (0.205–0.243)
	Fixed	0.206 (0.190–0.211)	0.187 (0.183–0.199)
PVF (%BW)	Normal	65.85 (64.16–66.95)	67.30 (58.04–69.68)
	Unfixed	60.76 (60.49–61.41) *	56.69 (54.56–57.58) *
	Fixed	76.45 (73.31–77.91) *	57.87 (54.60–63.56)
PPF (%BW)	Normal	9.08 (8.19–12.77)	9.67 (7.10–12.43)
	Unfixed	10.43 (9.59–14.08)	14.83 (9.17–18.03)
	Fixed	14.82 (12.46–16.26) *	6.21 (1.70–9.36)
PBF (%BW)	Normal	2.24 (1.00–2.76)	1.48 (1.21–3.48)
	Unfixed	1.75 (1.39–3.00)	1.51 (1.28–2.16)
	Fixed	1.36 (0.32–2.24)	3.67 (1.07–4.46)
VI (%BW·sec)	Normal	7.39 (6.96–7.47)	7.12 (6.42–7.80)
	Unfixed	7.11 (6.29–7.80)	6.40 (5.83–7.59)
	Fixed	8.12 (7.32–8.33)	6.16 (5.89–6.73)
PI (%BW·sec)	Normal	0.83 (0.74–1.17)	0.86 (0.53–1.10)
	Unfixed	1.01 (0.74–1.35)	1.38 (0.77–1.86)
	Fixed	1.33 (1.03–1.53) *	0.44 (0.13–0.93)
BI (%BW·sec)	Normal	0.096 (0.031–0.186)	0.065 (0.048–0.146)
	Unfixed	0.061 (0.030–0.117)	0.023 (0.015–0.119)
	Fixed	0.031 (0.003–0.053) *	0.174 (0.028–0.244)
Falling distance of ILI (mm)	Normal	20.6 (15.8–22.6)	23.4 (12.5–30.4)
	Unfixed	25.9 (21.8–32.4) *	18.1 (15.1–24.1) *
	Fixed	35.4 (30.8–40.3) *	19.0 (15.5–31.0)
Upward distance of ILI (mm)	Normal	19.8 (14.3–21.3)	21.6 (17.5–27.6)
	Unfixed	22.1 (18.4–27.0)	20.6 (18.4–27.0)
	Fixed	24.1 (22.9–29.0) *	25.1 (13.4–28.8)
Range of motion (degrees)	Normal	68.0 (54.5–73.5)	-
	Unfixed	53.8 (49.5–56.1) *	-
	Fixed	35.2 (25.7–38.9) *	-
Trotting velocity	Normal	0.897 (0.855–0.965)	
	Unfixed	0.818 (0.801–0.914) *	
	Fixed	0.867 (0.825–0.940)	

Normal: gait without the orthosis. Unfixed: gait with the orthosis that did not fix the stifle joint angle. Fixed: gait with the orthosis of which stifle angle was fixed at 135°. Trotting velocity was normalized with withers height (n=four beagles). BI, braking impulse; BW, body weight; ILI, ilium marker; PBF, peak braking force; PI, propulsive impulse; PPF, peak propulsive force; PVF, peak vertical force; ST, stance time; VI, vertical impulse. *$P<0.05$ compared to normal gait.

or upward distance of the ILI and the three gaits to identify a model containing variables whose coefficients significantly differed from 0. The right and left sides were separately evaluated. Interactions between variables were checked by performing likelihood ratio tests contrasting models with and without the interactions. Any clinically important or statistically significant interaction was included in the model. Stata (STATA, version 14, StataCorp. LP, College Station, TX, USA) was used for all analyses. For statistical estimation and inferences, two-sided hypothesis tests were used with a 5% significance level.

The median number of valid trials for each hindlimb was 5 (4–9) per experiment. The median values with ranges are listed in Table 1. The results of the multiple regressions for the right hindlimbs are shown in Table 2. In the right hindlimb, the PVF of fixed gait was 10.4%BW larger than that of normal gait ($P<0.01$). The PPF ($P<0.01$) and PI ($P=0.042$) of fixed gait were 5.30%BW and 0.435%BW·sec larger than those of normal gait, respectively. The BI of fixed gait was 0.0886%BW·sec smaller than that of normal gait ($P=0.017$). The falling distance of ILI ($P<0.01$) and upward distance of ILI ($P=0.033$) were 16.4 mm and 6.47 mm larger than those of normal gait, respectively. Also, in the right hindlimb, the PVF of unfixed gait was 4.56%BW smaller ($P<0.01$) and the falling distance of ILI was 8.66 mm larger ($P=0.042$) than those of normal gait. The results of the multiple regressions for the left hindlimbs are shown in Table 3. In the left hindlimb, the PVF ($P=0.059$) and VI ($P=0.051$) of fixed gait were 7.06%BW and 1.06%BW·sec smaller than those of normal gait, respectively. The PPF of fixed gait was 4.92%BW smaller ($P=0.079$) and the PBF of fixed gait was 1.62%BW larger ($P=0.101$) than those of normal gait, respectively, but they were not significant. Further, in the left hindlimb, the PVF of unfixed gait was 9.18%BW smaller ($P=0.039$) than that of normal gait. The falling distance of ILI ($P=0.024$) and upward distance of ILI ($P=0.070$) were 11.6 mm and 8.90 mm smaller than those of normal gait, respectively.

There was a significant increase in the PVF of the right hindlimb during fixed gait compared to that of normal gait. This could

Table 2. Multiple regression models for the right hindlimb illustrating the association between ST, PVF, PPF, PBF, VI, PI, BI, falling distance of ILI, or upward distance of ILI and the three gaits (normal, unfixed, and fixed) including velocity as independent variable

Dependent variable / Independent variables		Coefficient	95% Confidence Interval		*P* value	R^2
ST (sec)						0.262
Gait	Unfixed	0.0197	−0.00662	0.0460	0.123	
	Fixed	0.00221	−0.0195	0.0239	0.821	
Velocity		−0.0275	−0.244	0.189	0.776	
Constant *		0.225	0.0294	0.420	0.029	
PVF (%BW)						0.956
Gait	Unfixed *	−4.56	−7.47	−1.66	<0.01	
	Fixed *	10.4	8.01	12.8	<0.01	
Velocity		3.88	−20.0	27.7	0.718	
Constant *		62.2	40.6	83.8	<0.01	
PPF (%BW)						0.531
Gait	Unfixed	2.54	−1.34	6.42	0.170	
	Fixed *	5.30	2.10	8.51	<0.01	
Velocity		16.1	−15.8	48.0	0.277	
Constant		−4.76	−33.6	24.1	0.713	
PBF (%BW)						0.0743
Gait	Unfixed	−0.632	−2.22	0.952	0.384	
	Fixed	−0.946	−2.25	0.362	0.134	
Velocity		−7.34	−20.4	5.66	0.229	
Constant		8.68	−3.08	20.4	0.127	
VI (%BW·sec)						0.236
Gait	Unfixed	−0.304	−1.39	0.779	0.536	
	Fixed	0.642	−0.252	1.54	0.136	
Velocity		−1.06	−9.95	7.83	0.791	
Constant *		8.26	0.218	16.3	0.045	
PI (%BW·sec)						0.224
Gait	Unfixed	0.190	−0.312	0.692	0.407	
	Fixed *	0.435	0.0205	0.849	0.042	
Velocity		0.807	−3.32	4.93	0.664	
Constant		0.166	−3.56	3.89	0.921	
BI (%BW·sec)						0.396
Gait	Unfixed	−0.0760	−0.158	0.00620	0.066	
	Fixed *	−0.0886	−0.156	−0.0208	0.017	
Velocity		−0.550	−1.22	0.125	0.097	
Constant		0.598	-0.0121	1.21	0.054	
Falling distance of ILI (mm)						0.722
Gait	Unfixed *	8.66	0.406	16.9	0.042	
	Fixed *	16.4	9.60	23.2	<0.01	
Velocity		27.3	−40.4	95.1	0.379	
Constant		−4.77	−66.0	56.5	0.862	
Upward distance of ILI (mm)						0.260
Gait	Unfixed	4.20	−2.83	11.2	0.206	
	Fixed *	6.47	0.669	12.3	0.033	
Velocity		7.68	−50.0	65.4	0.767	
Constant		11.8	−40.3	64.0	0.614	

For gaits, unfixed and fixed were compared to normal. BI, braking impulse; BW, body weight; ILI, ilium marker; PBF, peak braking force; PI, propulsive impulse; PPF, peak propulsive force; PVF, peak vertical force; R^2, adjusted coefficient of determination; ST, stance time; VI, vertical impulse. *P<0.05.

be due to significantly increased falling and upward distances of ILI. A higher lift-up of the caudal trunk during the swing phase of right hindlimb would be required to move the limb forward without deep knee flexion. The vertical movement of the trunk would greatly influence the PVF because the trunk comprises the largest portion of a dog's body and accounts for more than 60% of the total whole-body mass [2, 7]. Similarly, it was reported that some humans wearing orthoses that restrict knee movement lifted the body mass high by vaulting in order to move the stiff limb forward [4]. For unfixed gait, the PVF of the left hindlimb was significantly decreased corresponding to the decrease in the falling distance of ILI. However, the PVF of right hindlimb was also

Table 3. Multiple regression models for the left hindlimb illustrating the association between ST, PVF, PPF, PBF, VI, PI, BI, falling distance of ILI, or upward distance of ILI and the three gaits (normal, unfixed, and fixed) including velocity as independent variable

Dependent variable / Independent variables		Coefficient	95% Confidence Interval		*P* value	R^2
ST (sec)						0.541
Gait	Unfixed	0.0158	0.00854	0.0402	0.173	
	Fixed	−0.0114	−0.0324	0.00954	0.244	
Velocity		−0.119	−0.360	0.122	0.287	
Constant *		0.304	0.0843	0.524	0.013	
PVF (%BW)						0.413
Gait	Unfixed *	−9.18	−17.8	−0.570	0.039	
	Fixed	−7.06	−14.5	0.342	0.059	
Velocity		0.370	−84.8	85.6	0.992	
Constant		65.2	−12.4	143	0.089	
PPF (%BW)						0.523
Gait	Unfixed	2.58	−4.00	9.15	0.393	
	Fixed	−4.92	−10.6	0.729	0.079	
Velocity		−31.0	−96.1	34.0	0.304	
Constant		37.9	−21.4	97.3	0.179	
PBF (%BW)						0.174
Gait	Unfixed	0.269	−2.08	2.62	0.798	
	Fixed	1.62	−0.399	3.65	0.101	
Velocity		9.06	−14.2	32.4	0.396	
Constant		−6.34	−27.6	14.9	0.511	
VI (%BW·sec)						0.176
Gait	Unfixed	−0.878	−2.12	0.362	0.141	
	Fixed	−1.06	−2.13	0.00840	0.051	
Velocity		−5.11	−17.4	7.17	0.365	
Constant *		11.8	0.565	23.0	0.042	
PI (%BW·sec)						0.485
Gait	Unfixed	0.228	−0.526	0.982	0.505	
	Fixed	−0.513	−1.16	0.135	0.106	
Velocity		−4.53	−12.0	2.93	0.199	
Constant		4.96	−1.84	11.8	0.131	
BI (%BW·sec)						0.167
Gait	Unfixed	−0.00236	−0.156	0.151	0.973	
	Fixed	0.0926	−0.0395	0.225	0.145	
Velocity		0.536	−0.985	2.06	0.440	
Constant		−0.407	−1.79	0.980	0.518	
Falling distance of ILI (mm)						0.422
Gait	Unfixed *	−11.6	−21.2	−1.99	0.024	
	Fixed	−5.80	−14.0	2.46	0.144	
Velocity *		−129	−224	−34.2	0.014	
Constant *		140	53.3	227	<0.01	
Upward distance of ILI (mm)						0.299
Gait	Unfixed	−8.90	−18.7	0.906	0.070	
	Fixed	−2.79	−11.2	5.65	0.468	
Velocity *		−110	−207	−12.5	0.031	
Constant *		122	33.3	210	0.013	

For gaits, unfixed and fixed were compared to normal. BI, braking impulse; BW, body weight; ILI, ilium marker; PBF, peak braking force; PI, propulsive impulse; PPF, peak propulsive force; PVF, peak vertical force; R^2, adjusted coefficient of determination; ST, stance time; VI, vertical impulse. *P<0.05.

significantly decreased in unfixed gait, despite the increased falling distance of ILI. This result suggests that factors other than the falling or upward distances of ILI affect the PVF. One potential factor was the range of motion of the stifle joint. Since the stifle restriction might have resulted in insufficient stifle flexion to cushion the impact, it could have led to a large PVF. The orthoses limited the range of motion of the right stifle joint in both fixed and unfixed gait, but the restriction was weaker for unfixed gait. As the normal stifle range of motion of the stance phase was reported to be around 20° in previous studies [11, 16], the stifle restriction in the unfixed gait of the current study might not have affected the stifle range of motion in the stance phase. The stifle orthoses that were used in the treatment of cranial cruciate ligament rupture were reported to not restrict the stifle motion as expected [16]. Unlike the orthoses used in that study, the orthoses used in the current study were custom-made to fit each dog and the restriction with fixed gait was more consistent. We did not observe any skin injuries caused by the orthoses during the study period.

The significantly increased PPF and PI of the right hindlimb in fixed gait, along with the significantly decreased BI, indicated that the function of the right hindlimb with the fixed orthosis was shifted into propulsion. In contrast, the left hindlimb in fixed gait analysis demonstrated a trend of decreased PPF and increased PBF, suggesting a shift into braking function. Previous studies reported that PPF, PBF, and BI were decreased as velocity decreased in normal Greyhounds [10, 12]. It is suggested that an increase of propulsive function of the right hindlimb in fixed gait may be inexorable due to stifle restriction. The decreased propulsive force and increased braking force of the left side may counterbalance this increased propulsive function. Similar adaptations have been reported with induced forelimb lameness [1] and induced chronic hindlimb lameness [13], although the patterns of change were different in these cases. We did not observe the alteration of fore-aft ground reaction force in unfixed gait. A previous study using a computer model predicted that changes in the hinge stiffness of stifle orthoses would influence the ligament stabilizing effect in the stifle joint [3]. This study highlighted the importance of selecting a hinge that stabilizes but does not over-constrain the stifle joint when treating a cranial cruciate ligament rupture [3]. The findings of our study suggest that the level of constraint of the orthoses would also affect the ground reaction force pattern and over constraint might increase the load on some joints.

A previous study compared the gait of dogs with and without harnesses and revealed that wearing a harness restricts shoulder extension [8]. Another study compared the gait of dogs with and without service vests and revealed that wearing service vests reduced trunk motion [6]. Similar restrictions to the shoulders, left hip, or trunk could have existed in the current study, since the orthoses were designed to strap the cranial part of the trunk and proximal girth of the contralateral hindlimb with a soft cloth (Fig. 1). Some of the changes noted in the current study could have been caused not only by restriction of the right stifle but by wearing the orthosis itself. The other limitations of this study were the limited number and use of one breed of dogs, which were restricted due to limited kennel space and time constraints. These may be the reasons for the small adjusted coefficient of determination in the final multiple regression model for the VI, PI, BI, and upward distance of ILI.

In conclusion, restriction of the range of motion of the right stifle joint with orthoses changed the ground reaction force patterns of both hindlimbs. The vertical ground reaction force was affected by both unfixed and fixed orthoses. However, the PVF of the right hindlimb was increased with a fixed orthosis but decreased with an unfixed orthosis, which might be derived from the difference of the range of motion of the stifle joint. Furthermore, the fore-aft ground reaction force was also altered with the fixed gait but not with the unfixed gait. The alteration of ground reaction force varied with the restriction level of orthosis.

POTENTIAL CONFLICTS OF INTEREST. The authors have nothing to disclose.

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