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Treadmill vs. overground trotting - a comparison of two kinetic measurement systems

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ABSTRACT

Force plates are considered the gold standard for kinetic gait analysis, benefiting from measuring three-dimensional ground reaction forces. Nevertheless, the major disadvantage is that many trials are required during overground locomotion to capture adequate single-limb contacts. Additionally, the dogs slightly change velocities during overground walking, influencing kinetic and kinematic gait parameters. An alternative is using an instrumented treadmill that benefits from capturing many steady-state gait cycles at a constant speed quickly. The goal of this study was (1) to compare overground with treadmill locomotion and (2) to compare the instrumented treadmill with force plates for dogs kinetics measurements.

Twelve client-owned dogs were measured during treadmill trotting while the treadmill was placed on force plates. Additionally, the dogs were measured during trotting along an alley over eight force plates. Bland-Altman plots, Pearson's (r), and concordance correlation coefficients (r_c) were computed to explore the relative and general agreement between the measurement methods and overground and treadmill trotting.

Overground and treadmill trotting gave an excellent agreement in peak vertical forces and impulses ($r > 0.9$, $r_c > 0.9$). The instrumented treadmill showed similar force-time curves in shape and size and provided an excellent congruity for all parameters compared to force plates ($r > 0.8$, $r_c > 0.8$).

As a reliable tool in measuring key gait parameters, the instrumented treadmill may benefit from fast and reproducible data comparable to overground trotting.

1. Introduction

Ground reaction forces (GRF) are well established in describing canine locomotion and identifying lameness. Force plates are considered the gold standard for kinetic gait analysis, benefiting from measuring three-dimensional GRF. Nevertheless, the major disadvantage is that many trials are required during overground locomotion to capture adequate single-limb contacts. Still, trial repetition is the primary source of variance (Jevens et al., 1993). The use of more than one force plate may decrease the number of trials for overground gait data acquisition (Stejskal et al., 2015), but at the same time, the already high acquisition costs and space required increase. Additionally, when guiding the dog over the force plates, uncontrollable variations of traveling speed affect the stance phase duration, thus the forces and impulses. Furthermore, the use of force plates is only possible to a limited extent in everyday clinical practice. Therefore, the development of other gait systems was encouraged, such as pressure walkways (Besancon et al., 2003; Kim et al., 2011; Lascelles et al., 2006; Lequang et al., 2010; Light et al., 2010; Schwarz et al., 2017) and instrumented treadmills (Assaf et al., 2019; Bockstahler et al., 2007; Brebner et al., 2006; Häusler et al., 2020; Off and Matis, 2010).

Instrumented treadmills benefit from capturing many steady-state gait cycles at a consistent speed quickly (40 walking gait cycles of a medium-sized dog in 30-s measurement (Häusler et al., 2020)). A repeatable steady-state gait (e.g., habituation), regarding force and impulse values for walking and trotting, occurred within the first day of training (Fanchon and Grandjean, 2009; Häusler et al., 2020; Pietsch et al., 2020). Additionally, kinetic measurements' reproducibility was good, indicated by a low coefficient of variation (Fanchon and Grandjean, 2009; Pietsch et al., 2020). Repeatability among and within days for kinetic data was good (Bockstahler et al., 2007) and was confirmed by Häusler et al., 2020, considering dogs above 15 kg.

Using an instrumented treadmill for kinetic investigation is rarely done in canine biomechanics. Since instrumented treadmills are

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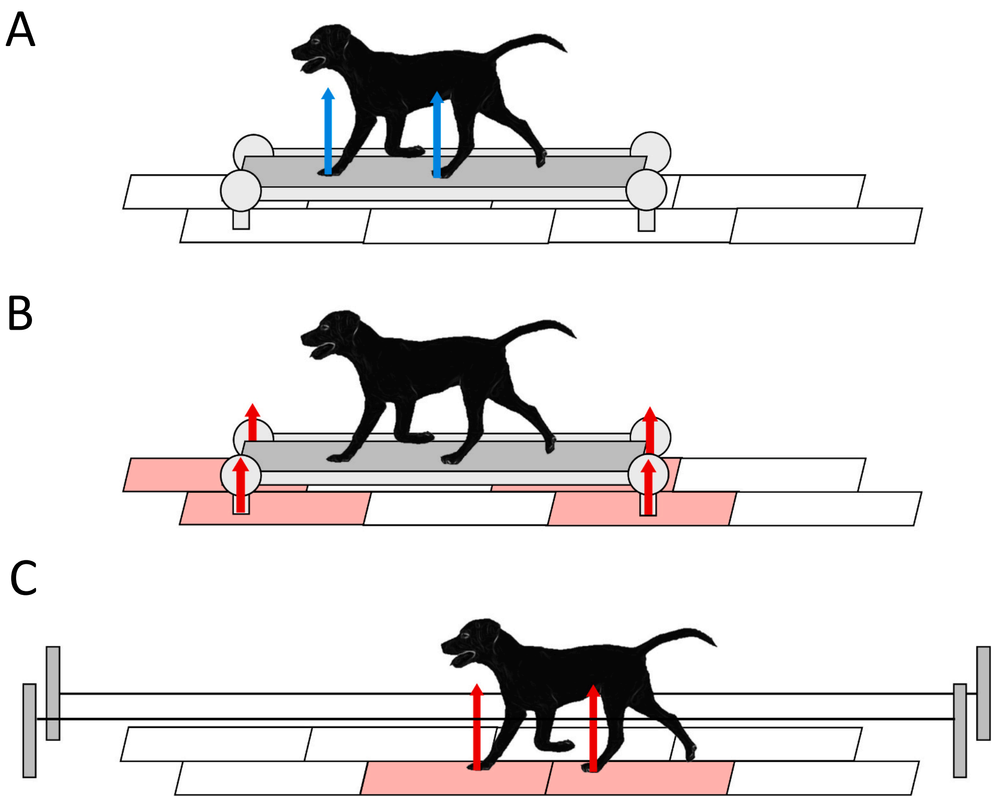

Fig. 1. Schematic representation of the experimental setup. A) "instrumented treadmill" locomotion. B) "treadmill on force plates" locomotion. C) "overground force plates" locomotion. Red arrows represent the vertical ground reaction force captured by the force plates, and active force plates are colored red. Blue arrows represent the vertical ground reaction force captured by the instrumented treadmill. Data comparison was made between A) and B) as well as B) and C). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Mean (±SD) values for each gait parameter of the average over ten gait cycles for diagonal limb pairs during "instrumented treadmill", "treadmill on force plate", and "overground on force plate".

Variable	instrumented treadmill locomotion	treadmill locomotion	Overground locomotion
PF_z [N]	524 ± 67	561 ± 71	548 ± 72
I_z [Ns]	74.9 ± 9.6	77.4 ± 9.7	73.9 ± 10.0
ts [s]	0.261 ± 0.006	0.261 ± 0.007	0.250 ± 0.011
Cadence [Hz]	3.8 ± 0.1	3.8 ± 0.1	3.9 ± 0.2
SI [%]	2.44 ± 2.11	2.91 ± 2.45	2.66 ± 1.98

PFz: peak vertical force; Iz: vertical impulse; ts: stance duration; Cadence: step frequency; SI: Symmetry index of peak vertical force.

frequently used in locomotion research, the question raised whether treadmill gait is similar to overground gait. Bockstahler et al. (2007) found that forces are similar in size and shape to overground walking. Brebner et al. (2006) showed substantial to moderate agreement between mean peak vertical forces of overground trotting and treadmill trotting. Drüen et al. (2010) showed no significant difference in peak vertical force and vertical impulse in the hindlimbs and moderate correlation between overground and treadmill gait. However, there was no direct comparison of both measurement methods, leading to bias resulting in a lower agreement between the two systems (Brebner et al., 2006). Häusler et al. (2020) have shown that an instrumented treadmill was causing a systematic error, which increased with increasing belt speed (Häusler et al., 2020). A recent study found no significant difference in body weight distribution between the pressure-sensitive walkway and the treadmill but increased percentage stance duration on the treadmill. Decreased percentage swing duration and stride length were measured on the pressure walkway. A comparison of peak vertical forces and impulses was missing (Assaf et al., 2019).

This paper aims (1) to compare the kinetics of overground and treadmill trotting dogs recorded with two different measurement systems. Twelve dogs were measured during overground trotting on the force plates and trotting on the instrumented treadmill. (2) The instrumented treadmill was placed on force plates, allowing comparison of both recordings. Moreover, get a statement about the instrumented treadmill data's reliability compared to the force plate data. Based on the findings of Häusler et al. (2020), we assume a systematic error of up to 14% of the instrumented treadmill compared to force plate data during trotting. We hypothesized good to excellent agreement and correlation of overground and treadmill gait with a mean difference under 5%, due to the exact measurement equipment (Brebner et al., 2006).

Table 2
The difference of "overground force plate" vs. "treadmill force plate" locomotion, along with 95% limits of agreement (LoA), Pearson's correlation coefficients (r), and concordance correlation coefficients (r_c). Percentage difference and percentage limits of agreement are in relation to the overground data.

Parameters	Absolute difference (95% CI)	Percentage difference (95% CI)	Percentage LoA low (95% CI)	Percentage LoA upper (95% CI)	r (95% CI)	r_c (95% CI)
PF_z	−13.4 (−25.64, −1.17)	−2.68 (−4.94, −0.43)	−13.15 (−17.03, −9.27)	7.79 (3.91, 11.67)	0.92 (0.82, 0.96)	0.9 (0.79, 0.96)
I_z	−3.46 (−4.91, −2.01)	−4.96 (−7.04, −2.88)	−14.60 (−18.18, −11.03)	4.68 (1.11, 8.26)	0.94 (0.86, 0.97)	0.88 (0.77, 0.94)
ts	−0.010 (−0.013, −0.007)	−4.14 (−5.41, −2.87)	−10.04 (−12.22, −7.85)	1.75 (−0.44, 3.93)	0.72 (0.45, 0.87)	0.41 (0.19, 0.59)
Cadence	0.047 (−0.001, 0.10)	1.08 (−0.30, 2.46)	−5.31 (−7.68, −2.94)	7.48 (5.11, 9.85)	0.75 (0.50, 0.89)	0.51 (0.32, 0.66)

PFz: peak vertical force; Iz: vertical impulse; ts: stance duration; Cadence: step frequency.

Table 3
Difference of “instrumented treadmill” vs. “treadmill on force plate” locomotion along with 95% limits of agreement (LoA), Pearson's correlation coefficients (r), and Lin's concordance correlation coefficients (r_c).

Parameters	Absolute difference (95% CI)	Percentage difference (95% CI)	Percentage LoA low (95% CI)	Percentage LoA upper (95% CI)	r (95% CI)	r_c (95% CI)
PF_z	38.08 (34.21, 41.96)	6.80 (6.18, 7.41)	3.96 (2.90, 5.01)	9.63 (8.51, 10.69)	0.99 (0.98, 1.0)	0.86 (0.76, 0.92)
I_z	2.44 (1.70, 3.19)	3.15 (2.25, 4.06)	−1.06 (−2.63, 0.50)	7.37 (5.81, 8.94)	0.98 (0.96, 0.99)	0.95 (0.90, 0.98)
ts	0.00 (−0.002, 0.002)	−0.11 (−0.76, 0.54)	−3.14 (−4.26, −2.02)	2.92 (1.79, 4.04)	0.84 (0.65, 0.93)	0.82 (0.65, 0.92)
Cadence	−0.01 (−0.03, 0.01)	−0.27 (−0.71, 0.17)	−2.31 (−3.08, −1.56)	1.77 (1.01, 2.53)	0.94 (0.86, 0.97)	0.89 (0.80, 0.94)

PFz: peak vertical force; Iz: vertical impulse; ts: stance duration; Cadence: step frequency.

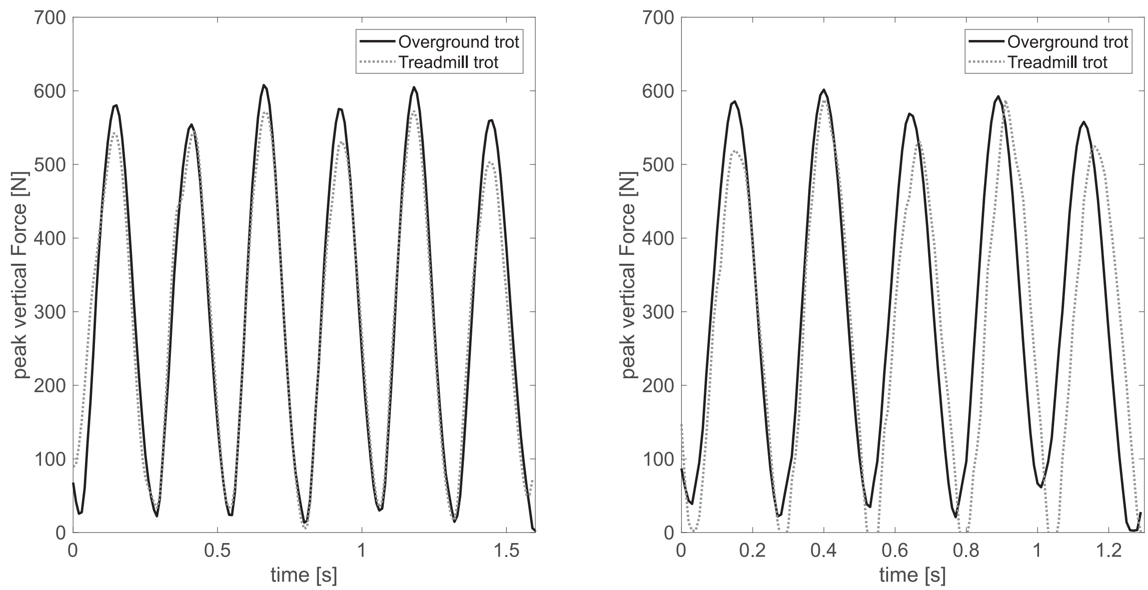

Fig. 2. Force-time curves of dogs locomotion “ treadmill on force plate” (dashed grey) and “overground on force plate” (solid). Left: Six steps were measured during one trial of one female dog (31 kg). The diagonal limb asymmetry is more pronounced during treadmill locomotion (6.25%) than overground locomotion (5.69%). Right: Five steps were measured during one trial of one female dog (32.4 kg). Diagonal limb asymmetry for overground (6.66%) and treadmill locomotion (8.73%). Note that treadmill and overground data are no simultaneous measurements.

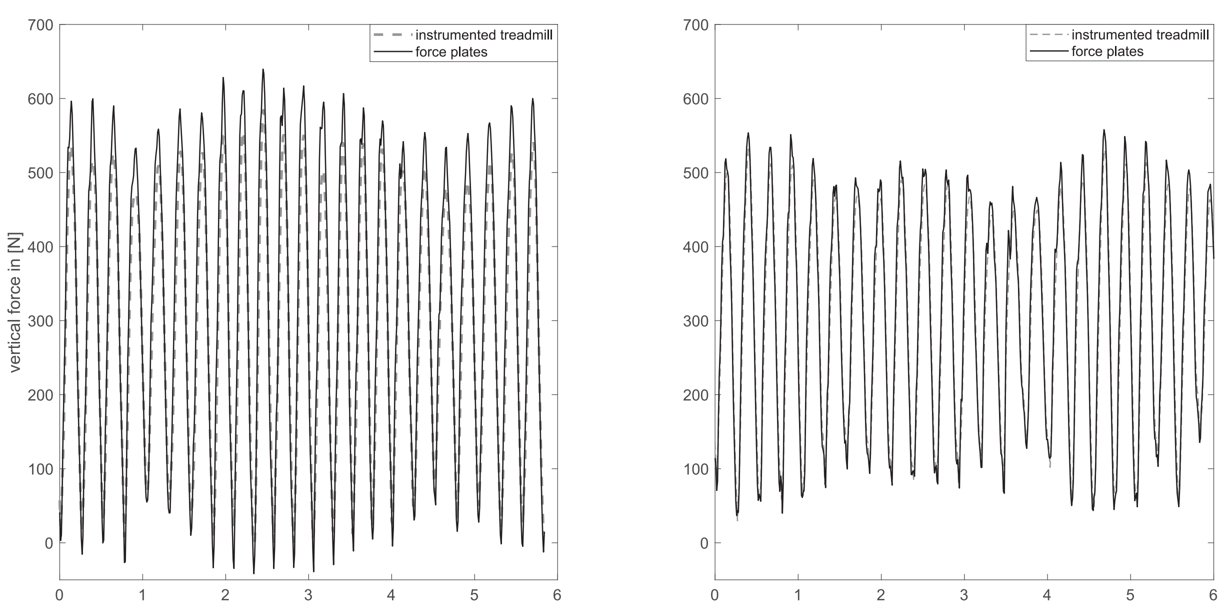

Fig. 3. Force-time curves for dogs locomotion “instrumented treadmill “(dashed grey) and “treadmill on force plate” (solid black). Left panel: one female dog with the highest difference between both measurements. Right panel: one female dog with the lowest difference between both measurements.

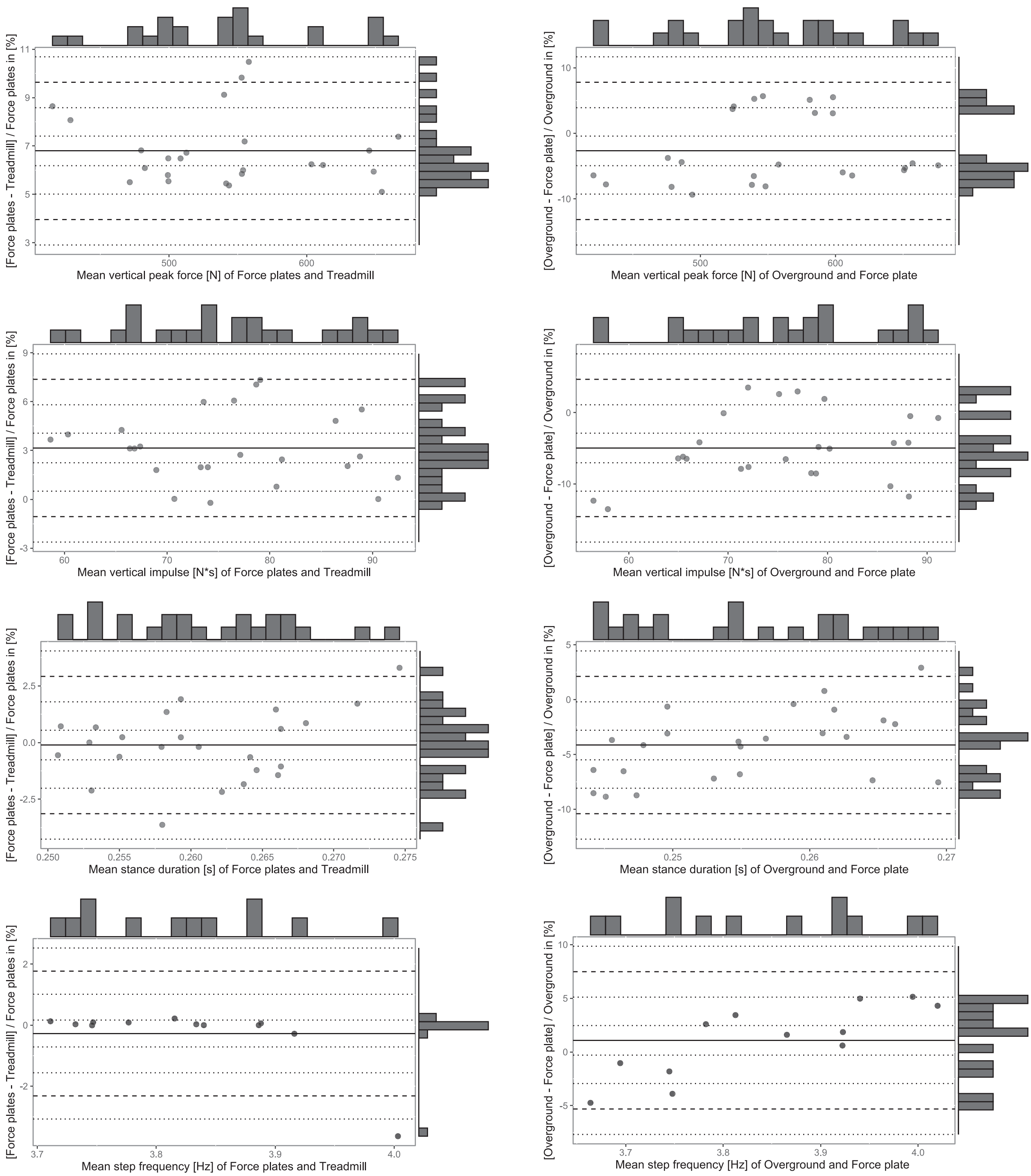

Fig. 4. Bland-Altman plots comparing measurements. Left: Percentage difference of "treadmill on force plate" and "instrumented treadmill" parameters over the mean of both. Right: Percentage difference of "overground on force plate" and "treadmill on force plate" parameters over the mean of both. First row: Peak vertical force. Second row: Vertical impulse. Third row: Stance duration; fourth row: Cadence.

2. Materials and methods

2.1. Animals

The study protocol was approved by "Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen" (LANUV) 81–02.04.2018. A327. Twelve pure breeds Labrador Retrievers were used. Five dogs were male, and seven dogs were female. Dog's body mass ranged from 24.47 kg to 36.07 kg (30.75 kg ± 3.45 kg), and their height at the withers was 53.9 cm ±1.5 cm. The age of the dogs ranged from one and a half years to seven and a half years (5.1 years ±2.2 years).

2.2. Data acquisition

The measurements took place in the OpenLab of the Westfälische Wilhelms Universität in Münster, Germany. The OpenLab is equipped with eight Kistler® force plates mounted in two rows in the walking track and covered with tartan to prevent slipping. Eighteen infrared Qualisys Oqus Cameras were set around the walking path, both systems were synchronized, and data were captured using Qualisys Trackmanager. An instrumented treadmill (Zebris CanidGait®) with an integrated pressure-sensitive matrix was placed on the force plates. Ten gait cycles were analyzed for each dog for the following instances as shown in Fig. 1: (A) "instrumented treadmill": capturing data from trotting on the instrumented treadmill. (B) "treadmill on force plate": capturing data from trotting on the treadmill placed on force plates. The four feet of the treadmill contacted four different force plates. The forces were transmitted through the treadmill feet, measured by the force plates during treadmill locomotion. The weight of the treadmill was discounted before force plate measurements started. (C) "overground on force plate": capturing data from guiding the dog through an alley over force plates. Records of (A) and (B) were done parallel, and data was synchronized per hand, allowing a direct comparison of the two measurement devices. For instance (C): An alley was built using thin ropes to ensure dogs trotted straight during overground locomotion. The same person led all dogs to eliminate interobserver variability. The time the dog needed from the beginning to the end of the alley was measured, and the speed was calculated using the alley's length. A valid trial was when the dogs trotted without pulling at the leash straight forward.

The sample rate of the instrumented treadmill was 100 Hz. The force plates were sampled with 12.000 Hz due to the need for per-hand synchronization of the force-time curves. Kinematic data were sampled at 480 Hz. Passive reflexive markers (diameter 12 mm) were used to identify which dog's limb was in ground contact. The anatomical positions for the eight markers attached to the dog were carpal joint, metacarpal joint, tarsal joint, and metatarsal joint, lateral and medial, respectively. Markers were glued at the dog using double adhesive tape and fixed with Kinesiotape®. The same person glued all markers to eliminate interobserver variability. One spherical marker was glued on the instructor's hand to detect the instrumented treadmill measurement start via touch screen due to no possible synchronization between the two measurement systems.

The habituation to trotting on the treadmill took place in two sessions. In the first session, dogs only walked for two minutes. After ten minutes of rest, dogs started walking, and speed increased in increments of 0.14 m/s for every 30 s until trotting at a maximum comfortable speed was achieved. A valid trial was when the dog was relaxed, trotting without pulling at the leash.

2.3. Data analysis

The trot is a cyclic gait, with the diagonal limb pairs in contact with the ground, clearly identifying ground contact of diagonal limb pairs. Data analysis was separated into the diagonal limb pairs. Force plates and instrumented treadmill deliver force-time data. The vertical force components of all force plates were summarized for "overground on force plate" (Fig. 1 C). The vertical components of the four force plates where the treadmill's feet were standing were summarized for "treadmill on force plates" (Fig. 1 B). Additionally, all limbs' vertical forces from the "instrumented treadmill" were summarized (Fig. 1 A). Data were compared between "overground on force plate" and "treadmill on force plate" to evaluate the locomotion difference. Additionally, the data from the "instrumented treadmill" was compared to the "treadmill on force plate" data, measured at the same time. Per-hand synchronization was used to match both measurements from treadmill locomotion and instrumented treadmill locomotion, allowing a direct comparison of both devices. Peak vertical force (PF_z), vertical impulse (I_z), stance duration (*ts*) for diagonal limb pairs, and stepping frequency (*cadence*) were analyzed for ten gait cycles. Calculating the symmetry index (SI) allows direct comparisons between the two collection methods of kinetic data in the dogs (Sandberg et al., 2018). The symmetry index (SI) of diagonal limb pairs was analyzed as:

$$\text{Symmetrie Index } (\%) = 100 - (\text{LFRH}/\text{RFLH})^{*}\ 100, \qquad (1)$$

Budsberg et al. (1993) showed that peak vertical GRF provided the most consistent symmetry indices. LFRH is the peak vertical force of the left-front and right-hind diagonal limb pair, and RFLH is the peak vertical force of the right-front and left-hind diagonal limb pair. An SI of 0 indicates perfect symmetry with this calculation. All analyses were done using Matalab® version 2017a.

2.4. Statistical methods

Means of ten gait cycles were calculated for each measurement per diagonal limb pair per dog. Pearson's (r) and concordance correlation coefficients (r_c) were computed to explore the relative and general agreement between the measurement methods. Specifically, Pearson's correlation assesses association irrespective of magnitude differences, whereas the concordance coefficient assesses both association and deviations from the identity line ($y = x$). Concordance correlation coefficients values <0.1 indicating no agreement and 0.1–0.4 slight, 0.41–0.60 fair, 0.61–0.80 substantial, and 0.81–1 almost perfect agreement (Koch and Spörl, 2007). Bland–Altman plots with (± 1.96 SD) agreement limits were calculated for all variables (see Fig. 4). All statistical analyses were done using open-Source R (version 4.0.4) and packages "DescTool" (version 0.99.040) and "epiR" (version 2.0.19) to calculate Lin's concordance correlation coefficient. The graphical display was done using package "ggplot2" (version 3.3.3) and package "ggExtra" (version 0.9) to plot the histogram.

3. Results

The study sample included twelve Labrador Retrievers (five male and seven female dogs), with a mean weight of 30.75 kg ± 3.45 kg. Dogs trotted at a comfortable speed on the treadmill and overground for ten regular gait cycles, respectively. Treadmill trotting velocity over all dogs was 1.89 m/s ± 0.07 m/s, while average overground trotting speed was slightly higher, 1.93 m/s ± 0.04 m/s. Two dogs could not trot overground in the velocity range from treadmill trotting, resulting in faster overground velocities by 0.39 m/s and 0.06 m/s, respectively. Instrumented treadmill measurements last 30 s to obtain ten regular gait cycles. During one "overground on force plate" trial, it was possible to capture a maximum of three complete gait cycles. Approximately 25 overground trials were used to capture ten regular gait cycles in the speed range from treadmill recordings. Values of diagonal limb pairs for each measurement are outlined in Table 1. The percentage error and agreement values from the Bland-Altman plot and correlation coefficients are provided in Tables 2 and 3.

"Overground on force plate" vs. *"Treadmill on force plate"*.

The mean difference of trotting on the treadmill and overground was under 5% compared for all analyzed parameters (see Table 2). Peak vertical force is 13.4 N or 2.7% higher during treadmill than overground trotting. All correlation coefficients revealed an excellent agreement between both measurements regarding the measured peak vertical force ($r > 0.9$, $r_c > 0.9$). The vertical impulse for diagonal limb pairs is 4.96% higher during treadmill trotting (absolute impulse 3.46 Ns) with an excellent correlation ($r = 0.94$, $r_c = 0.88$). The symmetry between diagonal limb pairs showed excellent correlation and agreement between the two measurement methods ($r = 0.92$, $r_c = 0.89$), with a mean difference of 5.1% (absolute symmetry index 0.25%). The asymmetry of diagonal limb pairs, therefore the symmetry index was higher during treadmill locomotion than overground locomotion, see Fig. 2 and Table 1.

The stance duration of diagonal limb pairs is approximately 4% longer during treadmill than overground trotting (absolute 0.01 s) and showed a substantial correlation and agreement ($r = 0.72$, $r_c = 0.41$). The step frequency was lower during treadmill trotting, and the difference is about 1.1% (0.05 Hz), with a substantial correlation ($r = 0.75$) between the two measurements and a fair agreement ($r_c = 0.51$).

"Instrumented treadmill" vs. *"Treadmill on force plate"*.

The force-time curves of both measurement systems were similar in shape and size, which means that manual synchronization could also be carried out well (see Fig. 3). Both methods showed almost perfect agreement for all measured parameters ($r_c > 0.81$, $r > 0.84$, see Table 1). The peak vertical force has the highest percentage difference of 6.8% (38 N). One dog crossed the upper agreement limit (see Fig. 3, left and Fig. 4 first row left) but is still inside the confidence interval. The vertical impulse, stance duration, and step frequency showed a difference under 5%, see Table 3.

4. Discussion

This study evaluated three different measurement methods in canine gait analysis. Twelve dogs trotted on an instrumented treadmill (Fig. 1 A), placed on force plates (Fig. 1. B), and during overground locomotion over force plates (Fig. 1 C). This is the first kinetic study that directly compared overground (C) and treadmill trotting (B) measured with the same force plates to prevent bias in the data. Additionally, a new instrumented treadmill (A) was compared with the "gold standard" of force plate measurements (B).

"Overground on force plate" vs. *"treadmill on force plate"*.

Overground and treadmill trotting gave an excellent agreement in peak vertical forces and impulses and a fair agreement in stance duration and *cadence*. Stance duration is approximately 4% longer during treadmill trotting. Assaf et al. (2019) found a longer percentage stance duration (concerning the whole gait cycle) during treadmill walking and related these differences to unequal surface conditions. Our study covered force plates with tartan, and the treadmill belt had a slip-proofed surface. It is more likely to relate the difference to the variability in overground trotting speed caused by trial repetitions of overground trotting that influence the gait's parameters (Riggs et al., 1993).

Furthermore, the *cadence* with increasing speed can cause the difference, which is 1% higher during overground trotting. Nevertheless, the Bland-Altman plot revealed no relevant outliers in all examined parameters, and the calculated difference is <5% for all values. The agreement limits are spread because of the higher variability in overground data (Jevens et al., 1993), but a good agreement should result in a standard deviation (SD) under 5%. Thus, we can assume that both gait measurements produce comparable results.

Additionally, limb symmetry is often used to assess lameness, with a symmetry index over 6% indicating lameness (Budsberg et al., 1993). We found one dog with an increased asymmetry of the peak vertical force of 6.66% during overground trotting accentuated during treadmill trotting (8,73%), see Fig. 2. Another dog showed an asymmetry of 5.69% during overground and 6.25% during treadmill trotting, indicating that asymmetries are more visible in treadmill locomotion, see Fig. 2. As already known, force plate data variation is majorly caused by trial repetition and can hide the limb asymmetries when averaging the data over the trials. Overground locomotion has the disadvantage that it is more often interrupted when dogs have to walk back and wait for the subsequent trial, giving the chance to recover, and so asymmetries might be obscured. Our results show that overground and treadmill measured forces are similar in shape and size (see Fig. 2 and Table 2), following findings by Bockstahler et al. (2007).

It is well known that GRFs are affected by breed, gender, body shape, trial repetitions, speed, habituation, and the gait examined. To reduce the factors that cause these variations, we used one breed, stereotyped habituation to treadmill and overground, one gait, were trying at best to match the comfortable speed in overground and treadmill locomotion, and finally used the same measurement devices.

"Instrumented treadmill" vs. *"Treadmill on force plate"*.

The Bland-Altman plots show a difference in the vertical GRF between the force plates and the instrumented treadmill of up to 40 N, corresponding to a difference of 6.8% per diagonal limb pair. One possible reason could be the much higher sample rate of the force plates, resulting in a better resolution of the peak vertical forces. Another possible reason could be interference, where the dog matches such a frequency that the treadmill starts swinging, as seen in Fig. 3 (left graph), where the force measured with the force plates reached negative values when unloaded. Concordance correlation and correlation coefficients showed almost perfect agreement (r_c for all parameters >0.8). In horses, force data from an instrumented treadmill was highly correlated with the force data measured by hooves shoes (Weishaupt et al., 2002). Thus, we can confirm that an instrumented treadmill can accurately measure the dog's key gait variables and is a suitable tool in assessing comparable gait parameters in a short time.

5. Conclusions

Overground and treadmill gait parameters seem to be slightly different, caused by higher variability of overground locomotion. Nevertheless, overground and treadmill locomotion showed good agreement. The instrumented treadmill measures kinetic gait parameters quickly, and asymmetries seem to be better detected during treadmill gait. Therefore, it is a suitable tool for experimental and clinical investigations.

Declaration of Competing Interest

Heel's Fund played no role in the study design nor the collection of data, analysis, interpretation of data, nor the decision to submit the manuscript for publication. In addition, none of the authors has any other financial or personal relationships that could inappropriately influence or bias the paper's content.

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