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STATIC WEIGHT DISTRIBUTION ON DRY LAND AND GAIT CHARACTERISTICS AND HEART RATE RESPONSE OF HEALTHY DOGS DURING PARTIAL-WATER IMMERSION ON A TREADMILL

By

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To the Graduate Faculty:

The members of the committee appointed to examine the thesis of Katrina Cassidy Davis find it satisfactory and recommend that it be accepted.

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LIST OF ABBREVIATIONS

ANOVA — analysis of variance

ANCOVA — analysis of covariance

bpm — beats per minute

fps — frames per second

HP — horsepower

PCA — principal components analysis

MANOVA — multivariate analysis of variance

ABSTRACT

The incidence of musculoskeletal problems is nearly 1 in every 4 dogs that visit a veterinary clinic. There are not many methods to quantify these conditions, nor is there a good understanding of how certain treatments affect these animals. This thesis presents techniques to detect musculoskeletal conditions through a static weight measuring system, and examines whether previously injured dogs and those with turned heads during measurements have normally distributed data, including static weight distribution and two-dimensional center of mass. The second chapter describes research using an underwater treadmill and determines what partial-water immersion does to the gait characteristics and heart rate of healthy dogs. These studies add fundamental knowledge about systems and techniques to detect and monitor musculoskeletal conditions, as well as define how hydrotherapy on a treadmill affects the gait of dogs. Ultimately this new information may improve the diagnosis and treatment of musculoskeletal conditions in dogs.

INTRODUCTION

A study of veterinary teaching hospitals throughout United States and Canada estimated that 24% of dogs seen in veterinary clinics had some type of musculoskeletal disorder (Johnson et al., 1994). Over 70% of those dogs had an injury or disorder affecting their limbs. With so many cases of musculoskeletal injury, an important goal of clinical and basic research is to develop better techniques to detect, treat, and monitor such conditions. Recently, some strides have been made using force platforms to determine ground reaction forces in dogs with induced lameness (Rumph et al., 1995), cranial cruciate ligament tears (Budsberg et al., 1988), osteoarthritis (Kennedy et al., 2003) as well as other conditions. Ground reaction forces can detect lameness in moving dogs, but they have not been measured during quiet standing. Although a sentinel study on postural stability during standing was published in 1965 by Brookhart et al., static measurements of dog weight distribution have been largely overlooked in favor of walking or trotting dogs, in order to exacerbate musculoskeletal disorders and increase chances for detection.

There may be some important advantages to measuring static weight distribution to detect lameness. First, measurement of static weight distribution is easier and more cost effective, especially for larger animals. A recent study on dairy cattle was able to detect lameness via static weight measurements by comparing contralateral limb weight distribution ratios (Pastell et al., 2010). In addition, an unpublished study by Chalayon and colleagues (2013) showed that lame dogs had a different static weight distribution when compared to healthy dogs. Specifically, 4 dogs with musculoskeletal conditions differed in front to back weight distribution by more than 5% from the average (63:37%), and the left to right distribution was between 6 and 48% different from a 50:50 distribution for 9 dogs with musculoskeletal conditions. Second, measurement of static weight distribution during quiet standing is a less painful way to detect lameness in dogs and should be further investigated. However, ground reaction forces differ among dog breeds during movement (Bertram et al., 2000; Voss et al., 2011) and there may be intrinsic differences in load distribution due to dog breed and size. With that in mind, the objectives for Chapter 1 included determining the effects of dog size, head position during measurements, and orthopedic health status on static measurements of weight distribution. The ultimate goal was to establish “normal” data for weight distribution and two-dimensional center of mass for healthy dogs. We hypothesized that dogs with previous injuries would have normal measurements. We also hypothesized that head position in the horizontal plane would have an effect on both static weight distribution and two-dimensional center of mass measurements. Dog size (in terms of body weight) could also influence weight distribution and we hypothesized that body weight would be correlated with the front to back distribution of weight and two-dimensional center of mass in dogs. Finally, we hypothesized that static weight distribution and two-dimensional center of mass would be similar for a given dog, but two-dimensional center of mass would be less variable than static weight distribution. Determining whether previous injury and head position affects these measurements will help future researchers set standards to compare injured dogs against, and illuminating the similarities and differences between static weight distribution and two-dimensional center of mass may indicate which measurement is more sensitive as a detection tool for orthopedic conditions.

Musculoskeletal conditions and lameness are very common among dogs, but it is unclear how certain treatments, such as hydrotherapy, affect the movement and cardiovascular functions of dogs. Hydrotherapy has become a popular veterinary tool in the United Kingdom (Waining et al., 2011) and is gaining support here in the United States as well. Hydrotherapy is effectively used to help humans recover from anterior cruciate ligament (ACL) injuries (Akiyama et al., 2010) and we understand some of the beneficial mechanisms of action. However, for dogs this is not as well understood. As a result, Chapter 2 of this thesis presents gait characteristics and heart rates of healthy dogs on an underwater treadmill during partial-water immersion at therapeutic temperatures, and compares the measurements to identical conditions in the absence of water. We hypothesized that, much like humans, dogs walking in water would experience several benefits. Firstly, dogs would expend more energy in water and reach a higher heart rate compared with the dry treadmill. We also hypothesized that gait characteristics would be affected by the partial-water immersion due to the buoyant effects of the water and the increased resistance to forward motion. With a better understanding of the effects of partial-water immersion on heart rate and gait during therapeutic exercise, clinicians will be in a better position to evaluate and prescribe hydrotherapy for dogs with a variety of conditions, such as obesity and those recovering from musculoskeletal injuries.

In summary, the high prevalence of musculoskeletal conditions in dogs is motivation to develop new techniques and standards for the detection and treatment of such conditions. Chapter 1 provides a simple instrument and analysis for the measurement of static weight distribution in healthy dogs, while Chapter 2, for the first time, demonstrates how partial-water immersion affects gait characteristics and heart rate in healthy dogs.

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CHAPTER 1:

Considerations for measurement of static weight distribution and two-dimensional center of mass in healthy dogs

ABSTRACT

Objective— Measure static weight distribution and two-dimensional center of mass for a diverse group of dogs, examine the effects of head position, previous injuries, and body weight on these variables, and compare the static weight distribution and two-dimensional center of mass measurements.

Animals— Owners of dogs competing in an agility trial volunteered 81 dogs of various breeds for this study. Dogs ranged from 3.3 kg to 41.8 kg and ages 6 months to 12.5 years old. Dogs were grouped according to head position, previous injuries, and body weight. Previous injuries ranged from minor athletic injuries and jammed toes, to tibia and fibula fractures.

Procedure— Dogs were grouped such that Group 1 included 80 dogs with all head positions and previously injured dogs, Group 2 had 54 non-injured dogs with all head positions, and Group 3 contained 51 non-injured dogs with only straight and slight horizontal head turns (less than 45˚ from center). A four balance system was used to obtain the static weight distribution of each dog while standing during 3-5 measurements. Digital cameras captured the foot placements during each measurement so that two-dimensional center of mass could be computed. The static weight distribution was normalized to % body weight placed on fore, hind, left and right limbs, and two-dimensional center of mass coordinates also were normalized for each measurement. A bivariate boxplot was used to visualize the data and possible outliers

within groups. MANOVA tests were performed to discern differences among head positions, and correlation tests were used to determine relationships between body weight and weight distribution.

Results— Just one measurement from one non-injured dog was outside the bivariate boxplot fence for the center of mass plot of Group 1. MANOVA tests revealed that head position affects both the static weight distribution and two-dimensional center of mass in Group 1 ($P < 0.05$), has a weak (non-significant) effect on Group 2, and a weak, but significant, effect on Group 3. The average % of weight placed on the fore:hind limbs was approximately 63:37%. Dogs placed ~47% of their weight on the right limbs on average. A correlation test revealed that dog body weight had a positive relationship with both the % weight placed on the hind limbs ($r^2 = 0.28$, 72 measurements, $p = 0.02$), and the *X* center of mass coordinate ($r^2 = 0.30$, 72 measurements, $p = 0.01$), while there was no relationship between dog body weight and weight placed on the right limbs ($r^2 = 0.09$, 72 measurements, $p = 0.46$) or the *Y* center of mass coordinate ($r^2 = 0.08$, 72 measurements, $p = 0.48$). The two-dimensional center of mass measurements are similar to the weight distributions proportionally, but are less variable in left to right distribution.

Conclusions and Clinical relevance— Consistent with previous research, on average dogs in this study distributed 63% of their weight to the front limbs and 37% to the hind limbs. However, there was asymmetry in left:right distribution because we included various head postitions. Head position does have an effect on both weight distribution and two-dimensional center of mass, and future studies should take head position into account when taking these measurements. All static weight distribution measurements from the 80 dogs of Group 1 fell inside the bivariate boxplot fence and only one non-injured dog measurement fell outside the two-dimensional center of mass boxplot fence. This suggests that the static weight distribution and two-dimensional center of mass of previously injured agility dogs are similar to non-injured agility dogs. The correlation tests of weight distribution and center of mass measurements for each dog did reveal a weak relationship between dog body weight and the % weight they place on the hind limbs, a similar weak relationship between body weight and the *X* center of mass coordinate (proportion of weight towards the back of the dog), no relationship between body weight and % weight placed on the right limbs or the *Y* center of mass coordinate (proportion of weight on the right side of the dog). This suggests that conformational or breed differences affect fore:hind limb weight distribution, but not the left:right distribution. Static weight distribution and center of mass measurements provided similar averaged results, but two-dimensional center of mass was less variable in the left to right distribution. This suggests that center of mass may be more resistant to changes brought on by head turning than static weight distribution, particularly in left to right distribution. With this information in mind, future studies should be conducted on specific breeds to establish normal weight distributions and variability. These measurements and corresponding databases should help detect lameness and quantify recovery from orthopedic conditions.

INTRODUCTION

A study by Brookhart and colleagues (1965) reported the first estimate of static weight distribution for dogs. The study included 4 dogs around 20 kg and the average weight distribution was roughly 60% on the front limbs and 40% on the hind limbs, with an equal distribution between left and right limbs. More recent studies have shown that certain conditions, such as cranial cruciate ligament tears (Budsberg et. al., 1988) and osteoarthritis (Kennedy et. al., 2003), produce measurable changes in forces exerted on the limbs of moving dogs. Similar studies also report differences in the ratio of vertical forces exerted on the moving fore and hind limbs of different breeds of healthy dogs (Bertram et. al., 2000; Voss et. al., 2011). Together these studies suggest that static measurements of weight distribution may be able to detect orthopedic conditions, but that breed differences among dogs must be considered.

Although certain conditions are known to produce changes in forces exerted on the limbs of moving dogs, the use of static measurements for purposes of detecting and following recovery of orthopedic conditions have not been published. Only an unpublished study, by Chalayon and colleagues (2013), included both healthy and lame dogs, and measured static weight distribution. They found that healthy dogs have a 63:37% weight distribution from fore:hind limbs with close to 50:50% distribution between left and right limbs. This study also illustrated that 4 lame dogs differed from these values by at least 5% in fore:hind limb distribution, and the 9 lame dogs had between 6 and 48% difference in left to right distribution. These data, although derived from just 25 dogs (15 healthy, 9 lame, and 1 obese), provide compelling evidence that static measurements of weight distribution can be used to detect lameness in dogs.

Compared with dynamic measurements of limb forces, static weight distribution and two-dimensional center of mass are simpler and less intensive measurements which can be used to detect lameness and orthopedic imbalance. However, basic knowledge about factors that affect these static measurements is required prior to successful application. For example, Do normal databases need to be concerned with the head position of dogs during measurements? Do the dogs need to be free of previous injuries? Can we create databases for multiple size categories, or do we need to create specific groups for dogs with similar body types? These questions should be answered before these measurement techniques can be used to detect any forms of lameness. Therefore, the first objective for the current study was to define potential effects of head position, dog size (body weight), and previous injuries on static weight distribution and normalized two-dimensional center of mass. A second objective was to compare two-dimensional center of mass measurements with the weight distributions. With this information more accurate databases can be created, and simple measurements of static weight distribution and two-dimensional center of mass can then be used by veterinary clinicians and researchers to quantify orthopedic compensation and monitor rehabilitation progress of injured dogs.

MATERIALS AND METHODS

Dogs— 81 animals were chosen randomly from a group of agility competitors, and the owners filled out a questionnaire before participating. Dogs with up-to-date vaccinations and no obvious signs of lameness were included in the study. There were a variety of dog sizes and breeds, with a maximum weight of 41.8 kg and a minimum weight of 3.3 kg. Dogs ranged in age from 6 months to 12.5 years old. Some of the dogs (27 of the 81, or 33%) had previous injuries, and these dogs were tagged for consideration during analysis. Previous injuries ranged from jammed toes and minor athletic injuries such as muscle strains, to tibia and fibula fractures early in life. Some injuries involved shoulder or carpal joints, one dog had cauda equine syndrome, another had a bulging disc in the spine, and another had hip dysplasia. Since the injuries were so diverse for these dogs, they were simply labeled as being previously injured or not.

Some dogs had measurements during which their heads were pointing up or down to receive a treat from their handlers, and because this usually produced changes in front to back weight distribution, those measurements were removed from the data. There were also measurements in which dogs placed a paw on two scales at the same time, and these measurements were also removed. One previously injured dog (# 67) that had a tibia and fibula fracture at 8 weeks of age produced measurements with consistently more weight on the front limbs. One of the measurements from this dog also caused the data to be non-normally distributed and we therefore removed that dog and all its trials from the data set.

Eighty dogs (not including dog 67) were included in Group 1 (all head positions during measurements, and those dogs with previous injuries). Group 2 consisted of 54 dogs that had not been previously injured, but included measurements with extreme head turns (more than 45˚ from center). Group 3 included 51 dogs with only slight head turns (less than 45˚ from center) or straight heads, and no previously injured dogs. We also separated Group 2 dogs into size categories based on a recent unpublished study (Chalayon et. al., 2013) for comparison. Dogs were considered small if they weighed 3-7 kg, medium if they were 7-20 kg, and large if they were 20 kg or more. There were 5 small dogs, 31 medium dogs, and 18 large dogs.

Scale system— As shown in **Fig. 1**, our weighing system included 4 digital scales[a], some foam/plastic mats taped to the top of each scale and labeled with 12.7 cm lengths of tape, a wooden frame with a shelf to hold the digital readouts, two particle board ramps, some carpets to cover the particle board and protect the feet of the dogs, a Plexiglas sheet with the white backing still on one side as a backdrop, and two agility jumps with long adjustable height bars used to help center the dogs on the scales. Finally, we also had three digital cameras set up around the system to capture the foot placements and digital scale readouts of weight distribution. The cameras were set up 1) 4.6 m directly in front of the dog, 2) 5 m directly to the left side of the dog, with the dog identification information written on the Plexiglas and the scale readouts visible in the digital image, and 3) 4.6 m directly behind the dog. The cameras were not linked, and we used a spotter to tell the camera operators when to take an image as the dog stood in the correct position. The handler attempted to keep the dog lined up with the scales, and the spotter tried to get the dog to look straight ahead, but some measurements resulted in turned heads, allowing us to determine whether head position affected static weight distribution.

Procedure— This study (number 700) was reviewed and approved by the Idaho State University Institutional Animal Care and Use Committee in accordance with the National Research Council Guide for the Care and Use of Laboratory Animals. Dogs were initially trained on our equipment by first having them walk across the scales, then having them stand still on them. Some dogs had a tendency to sit when stopped; therefore, training time varied for individual dogs and ranged from 1 to 10 min. When training was completed, dogs were led onto the scales and stopped when each foot was on a separate scale. It is important to note that dogs chose where to place their feet and we did not alter foot position during measurements. Dogs only went one direction through the scale system. Based on preliminary trial runs, the direction the dog was facing did not affect the measurement of static weight distribution or two-dimensional center of mass.

We were concerned with the head position of the dogs and tried to get them to look straight ahead during measurements. However, given that all dogs had at least one measurement with their head turned horizontally, we were able to address head

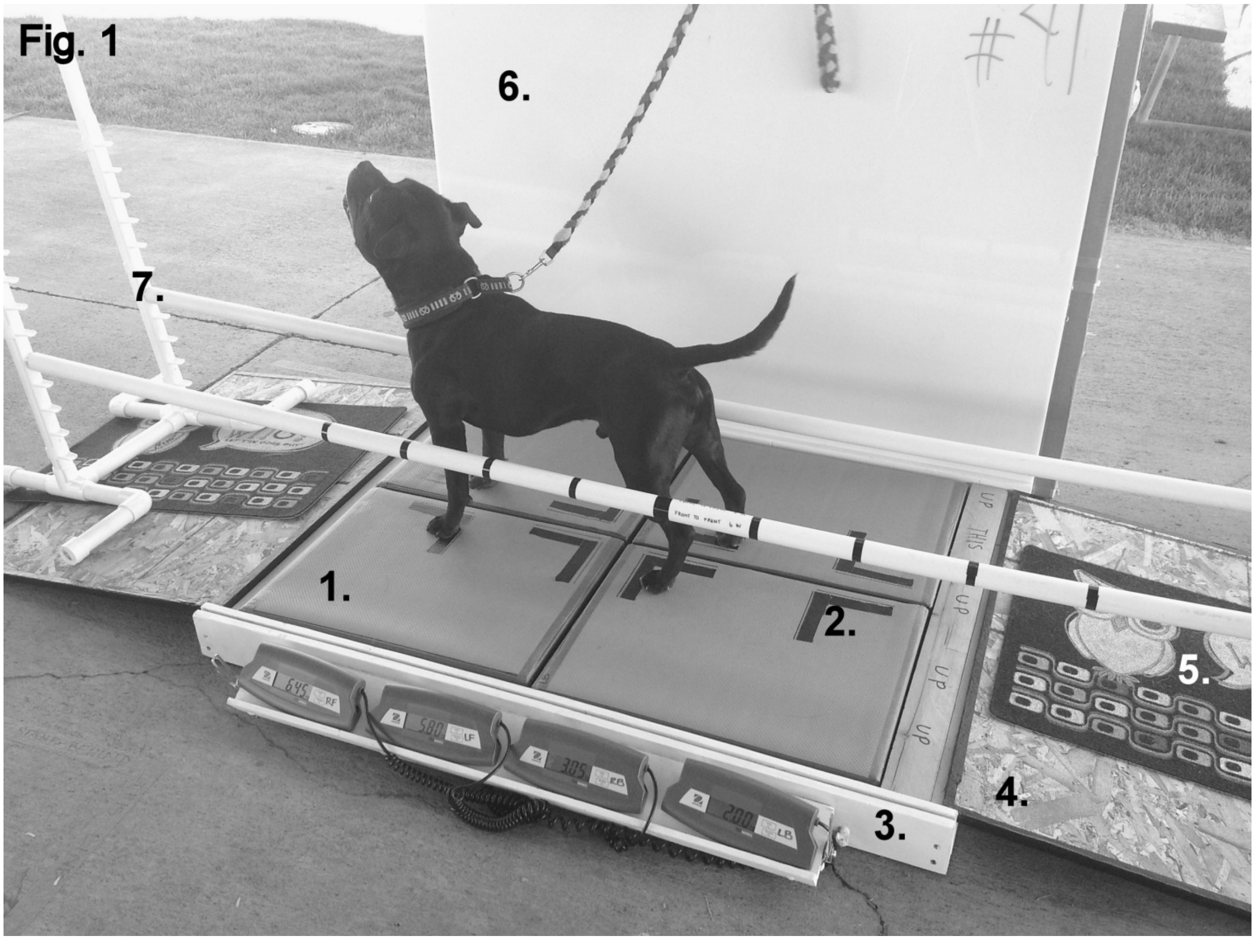

Figure 1— Static weighing system containing four balances topped with foam/rubber mats (1.), 12.7 cm long strips of tape placed on top of the mats in an L configuration for scaling reference (2.), a wooden frame which surrounds the four balances (3.) (and contains a shelf in front for the balance readouts), two particle board ramps on either side of the system (4.) covered by two rugs (5.) to protect the feet of the dog, a Plexiglas sheet with the backing still on one side to produce a backdrop (6.), and two adjustable PVC jump bars (7.) used sideways to channel the dog toward the center of the balances and promote straight head and body positioning. Dogs always entered with the Plexiglas sheet to their right as shown.

position and its effect on weight distribution and two-dimensional center of mass. To center the dogs on the balances and promote a straight head position we set up a lane with the jump bars. For each dog, we obtained at least 3 good measurements where the dog had each foot on a separate scale. Each dog took ~10 min to go through the training and measurement process. We collected data from 63 dogs at an outdoor covered venue in a single day. The rest were collected a different evening in a separate enclosed building.

Analysis of data—For each measurement we calculated the % of weight on the fore, hind, left, and right pairs of limbs for comparison. This data gave us information about the bilateral and front to back symmetry of static weight distribution. For purposes of determining two-dimensional center of mass we also used a computer program[b] to determine the distances between the feet of each dog in the digital images, for each measurement. The 12.7 cm pieces of tape on the mats topping the scale surfaces were used as references for measuring the distances in the images. Once the distances between each of the four feet were measured, foot placements were converted into (X,Y) coordinates with the left forelimb always at (0,0). The hind limbs were not always the same distance apart as the forelimbs, and neither were the left and right limbs; therefore, some automatic centering was done for those two distances on the Y axis and X axis respectively. With the weight measurements and coordinates in the correct format, we designed a program to compute two-dimensional center of mass and provide normalized center of mass coordinates for each dog and each measurement so that we could compare dogs with each other.

Calculating and normalizing two-dimensional center of mass—The center of mass of a three-dimensional body consisting of a distribution of masses is a vectoral quantity (meaning that it has direction and magnitude), and is given generically by a simple formula. If we let $\vec{r}$ denote a position vector with respect to any fixed frame of reference, and let $m(\vec{r})$ denote the contribution of the body's mass at location $\vec{r}$, then the center of mass of the body is given by:

$$\vec{r}_{cm} = \frac{\sum m(\vec{r})\, \vec{r}}{\sum m(\vec{r})} = \frac{1}{M_T} \sum m(\vec{r})\, \vec{r}$$

where M_T is the total mass of the body, and the sum taken over all mass elements comprising the body.

We fixed a coordinate system: with (*x*, *y*) denoting the location on the horizontal plane (with an origin (0, 0) fixed at the position of the left forefoot of the animal) and *z* denoting the vertical height above this plane. In our measurements of dogs, we did not have direct knowledge of the three-dimensional distribution of masses comprising the animal, but fortunately, the two dimensional projection of the center of mass onto the *x* − *y* plane could be found from the experimental data.

With $\vec{r}_{cm}$ being a vector quantity, ignoring the *z*-component of the position of the masses yields this two-dimensional $x - y$ projection. The measurements were the foot placement positions (call them $(x_1, y_1), \ldots, (x_4, y_4)$) and the corresponding weights measured at those locations (call those $w_1, \ldots, .w_4$). The weights were forces: $w_i = g\, m_i$, with g being the acceleration due to gravity ($980 cm/sec^2$). In essence the dog distributed its total mass (M_T) in terms of 4 submasses to each foot position, as reflected by the weight measured at that position.

The center of mass computation was straightforward:

$$x_{cm} = \frac{\sum_{i=1}^{4} w_i\, x_i}{\sum_{i=1}^{4} w_i} = \frac{\sum_{i=1}^{4} g\, m_i\, x_i}{\sum_{i=1}^{4} g\, m_i} = \frac{\sum_{i=1}^{4} m_i\, x_i}{\sum_{i=1}^{4} m_i}$$
$$y_{cm} = \frac{\sum_{i=1}^{4} w_i\, y_i}{\sum_{i=1}^{4} w_i} = \frac{\sum_{i=1}^{4} g\, m_i\, y_i}{\sum_{i=1}^{4} g\, m_i} = \frac{\sum_{i=1}^{4} m_i\, y_i}{\sum_{i=1}^{4} m_i}$$

Once computed, we had the x–y location of the animal's center of mass, but no knowledge of its z component or the three-dimensional center of mass.

To allow inter-sample comparisons, we introduced a dimensionless version of the centroid: the "normalized" center of mass. For each measurement of a given dog, we had the foot positions ($x1$, $y1$), . . . ,($x4$, $y4$). We then found the smallest bounding rectangle which contained all four of those locations: the breadth (x dimension) is given by B = max($x1$, $x2$, $x3$, $x4$) − min($x1$, $x2$, $x3$, $x4$), and the length (y dimension) is given by L = max($y1$, $y2$, $y3$, $y4$) –min($y1$, $y2$, $y3$, $y4$). We also kept record of x_{min} = min($x1$, $x2$, $x3$,

$x4$), and y_{min} = min($y1$, $y2$, $y3$, $y4$). The normalized center of mass was defined as an affine transformation of the raw coordinates (x_i, y_i). Letting (X, Y) denote the coordinates in the normalized system:

$$(X_i, Y_i) = (\ (x_i - x_{min})/B\ ,\ (y_i - y_{min})/L\ )$$

for i = 1, . . . , 4 (the normalized foot positions), and simultaneously

$$(X_{cm}, Y_{cm}) = (\ (x_{cm} - x_{min})/B\ ,\ (y_{cm} - y_{min})/L\ )$$

for the normalized center of mass.

Under this transformation, the foot positions of the dog always lie within the unit square [0, 1] × [0, 1], with at least one coordinate of some foot position on each edge of the square (it was the smallest such square containing all the data), and the centroid was always interior to this square (e.g., (X_{cm}, Y_{cm}) = (0.37, 0.48)). Note that the distance measurements along the X and Y axes are relative and independent of each other (X is normalized breadth, Y is normalized length). The advantage of the normalization was to be able to make comparisons between dogs of varying sizes and body conformations. The X coordinate for normalized center of mass represents the proportion of weight distributed to the hind limbs of a dog, while the Y coordinate is the proportion of weight distributed to the right limbs.

Statistical analysis—The % weight each placed on the hind limbs and the right limbs for each individual measurement were used to plot the static weight distribution in two dimensions. We plotted the % body weight on hind limbs and % body weight on right limbs of the individual measurements from each of the dogs, and the normalized *X* and *Y* center of mass coordinates from each measurement, with a bivariate boxplot[c] to construct a fence around the plotted data points. The inner fence, or hinge, encompassed 50% of the data points. Given infinite sampling, we would expect 99% of individual measurements to be on or inside the outer fence. We also calculated the 95% confidence intervals for the mean percentage of weight placed on the hind limbs and right limbs, as well as the center of mass coordinates.

Data from 80 dogs with all head positions (Group 1) were used to create bivariate boxplots using each individual measurement from these dogs to visualize static weight distribution and two-dimensional center of mass. Next, the previously injured dogs were removed, but all the head positions were included (Group 2) in the bivariate boxplot. Finally the data from the dogs with no previous injuries and only straight and slight head turns (Group 3) were summarized. Data from each of these groups were tested using MANOVA tests to determine if head position had an effect on weight distribution or center of mass coordinates. These data also were averaged by dog such that each dog had one average measurement and those averages were summarized. Dogs with no previous injuries (Group 2) were also placed into size categories (small dogs 3-7 kg, medium dogs 7-20 kg, and large dogs above 20 kg) and the individual measurements as well as the averaged data (by dog) were summarized and reported. Pearson's correlation tests were only performed on the measurements of non-injured dogs with straight head positions to determine whether body weight was correlated with the % weight placed on hind limbs, % weight placed on right limbs, the *X* center of mass coordinate, or the *Y* center of mass coordinate. All statistical analyses were performed using free software[c], and statistical significance was set at $P < 0.05$.

RESULTS

One dog (# 67) was removed from Group 1, and static weight distributions for each measurement of the 80 remaining dogs were plotted (**Fig. 2**). This plot revealed that dogs with previous injuries fit inside the bivariate boxplot with the other dog measurements. One measurement from a non-injured dog fell outside the bivariate boxplot fence of the center of mass plot for Group 1 (**Fig. 3**). The MANOVA tests performed on Group 1 (without dog 67) showed a significant effect of head position on static weight distribution ($P = 0.0056$), and center of mass ($P = 0.0075$). Static weight distribution measurements of Group 2 dogs with extreme head turns (>45˚ left or right) did not fall outside the fence or produce noticeable outliers (**Fig. 4**). The MANOVA test for Group 2, however, detected only a weak (non-significant) effect of head position on static weight distribution ($P = 0.052$), as well as center of mass ($P = 0.051$). The Group 3 MANOVA detected significant effects of head position on both static weight distribution ($P = 0.047$) and center of mass ($P = 0.035$).

The Pearson's correlation tests performed on 72 measurements from 39 non-injured dogs with straight heads revealed that dog body weight was positively correlated with the % weight placed on the hind limbs ($r^2 = 0.28$, 72 measurements, $P = 0.02$) and the *X* center of mass coordinates ($r^2 = 0.30$, 72 measurements, P = 0.01), while there was no relationship between dog body weight and % weight placed on the right limbs ($r^2 = 0.09$, 72 measurements, P = 0.46) or *Y* center of mass coordinates ($r^2 = 0.08$, 72 measurements, P = 0.48). The average % weight ratios placed on limb pairs for all individual measurements and for the averaged dog data are presented in **Table 1**. The data from Group 2 dogs according to size categories is summarized in **Table 2**.

The % weights placed on the hind limbs, and the *X* center of mass coordinates for all 81 dogs were not normally distributed (Shapiro-Wilk's, $P < 0.05$). These non-normal distributions were due to the measurements from the previously injured dog (#67), which was removed from Group 1. This dog placed more weight on the forelimbs than expected during measurements, and the data were normally distributed once measurements from this dog were removed.

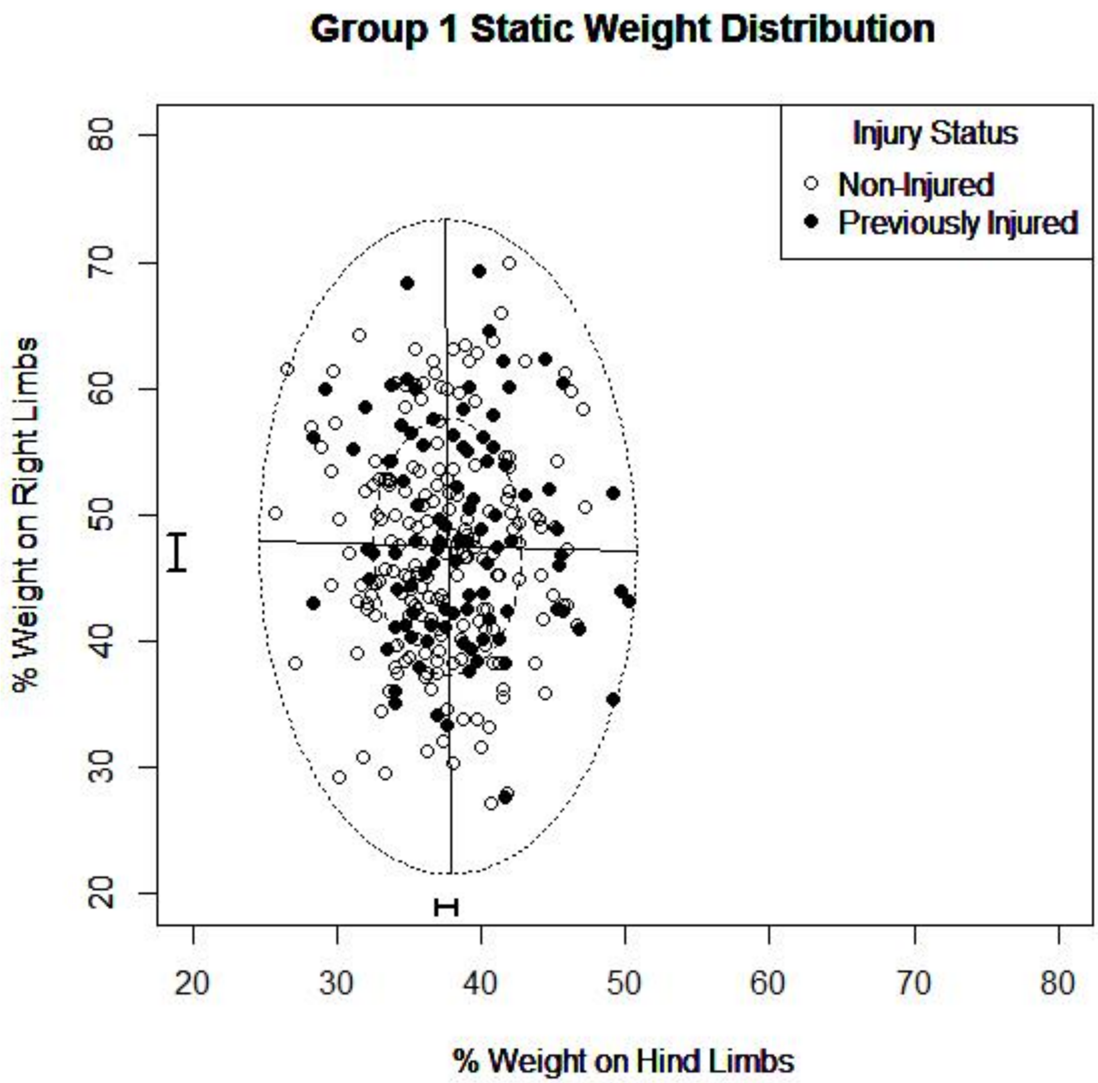

Figure 2— Bivariate boxplot with the % weight placed on hind and right limbs as (*x*,*y*) variables. This plot contains the individual measurements from 80 agility dogs (Group 1) with varying head positions. The measurements from dogs with previous injuries are labeled with black closed circles while non-injured dogs are shown with open circles. The outer fence can be thought of to contain 99% of all measurements if there was infinite sampling of this population. Thus any measurements outside the outer fence are likely outliers. The bars along the *x* and *y* axes are the 95% confidence intervals for the true means of each variable. Mean (± SD) % weight on hind limbs was 37.7 (± 4.4)% and the 95% confidence interval for that mean was 37.2-38.3%. Mean (± SD) % weight on right limbs was 47.6 (± 8.5)% and the 95% confidence interval for that mean was 46.6-48.6%.

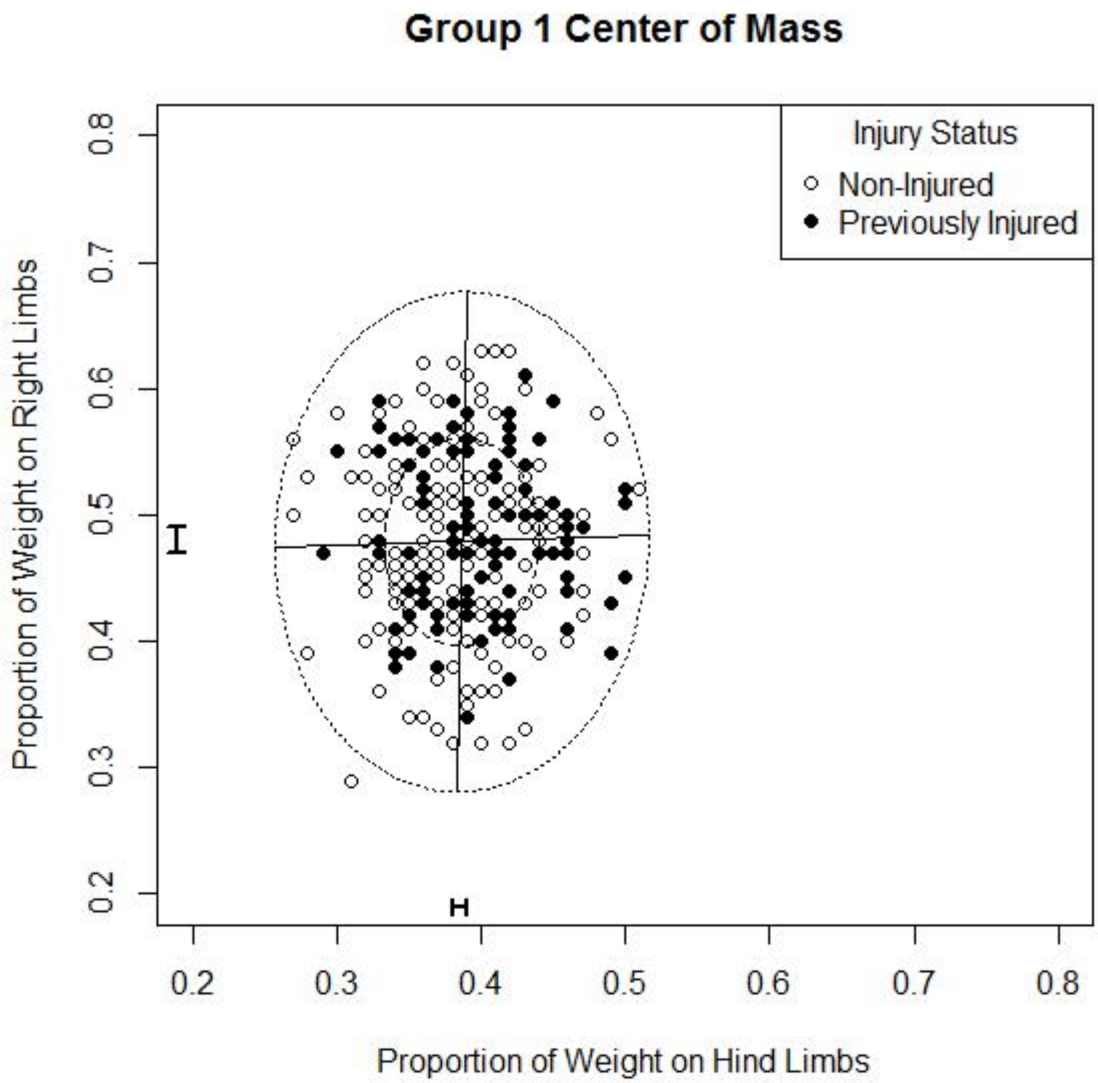

Figure 3— Bivariate boxplot of two-dimensional center of mass with the proportion of weight placed on hind and right limbs as (*x*,*y*) variables. This plot contains the individual measurements from 80 agility dogs (Group 1) with varying head positions. The measurements from dogs with previous injuries are labeled with black closed circles while non-injured dogs are shown with open circles. The outer fence can be thought of to contain 99% of all measurements if there was infinite sampling of this population. Thus any measurements outside the outer fence are likely outliers. The bars along the *x* and *y* axes are the 95% confidence intervals for the true means of each variable. Mean (± SD) proportion of weight on hind limbs was 0.387 (± 0.04) and the 95% confidence interval for that mean was 0.382-0.392. Mean (± SD) proportion of weight on right limbs was 0.479 (± 0.07) and the 95% confidence interval for that mean was 0.471-0.487.

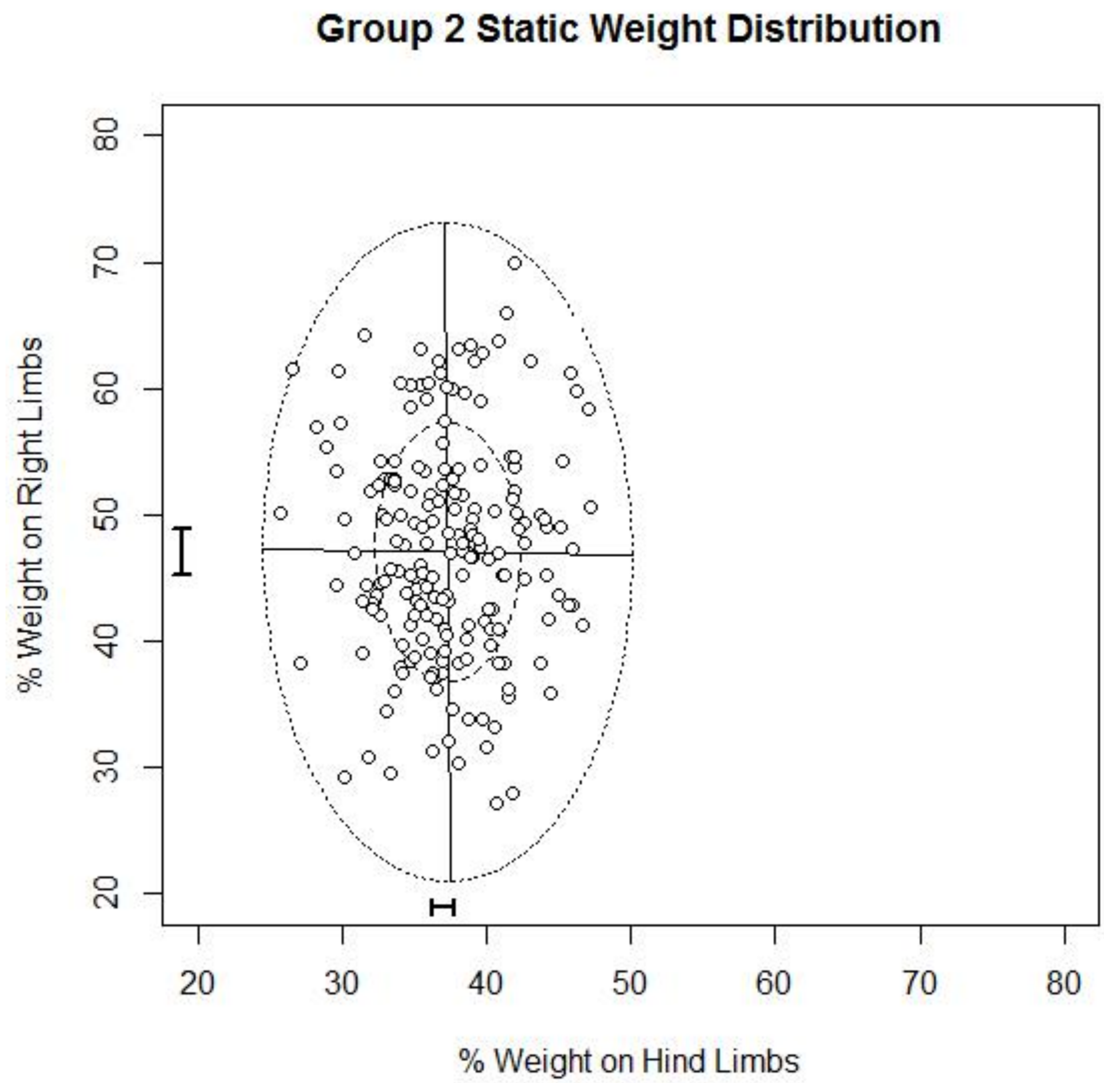

Figure 4— Bivarate boxplot of non-injured dog measurements. 54 agility dogs are included in this Group 2 plot with 3 or more measurements per dog. Far left and right head turns (past 45˚ from the center) are present in some measurements. None of the measurements are outside the boxplot fence. The bars along the axes show the 95% confidence interval of the mean for the two variables. The inner hinge of the boxplot contains 50% of the data, and the outer fence can be thought of to contain 99% of the measurements if there was infinite sampling from this population. Mean (± SD) % weight on hind limbs was 37.5 (± 4.7)% and the 95% confidence interval for that mean was 36.9 - 38.2%. Mean (± SD) % weight on right limbs was 47.3 (± 8.7)% and the 95% confidence interval for that mean was 46.1 - 48.6%.

Table 1— Weight distribution and normalized center of mass coordinates for a diverse group of agility dogs. Group 1 contained 80 agility dogs including various head positions and states of previous injury. Group 2 included any dogs that did not have a recorded previous injury (*n* = 54 dogs). Group 3 included dogs that did not have previous injuries, and any measurements where dogs turned their heads past 45˚ from center (to either left or right) were removed (*n* = 51 dogs). The 95% confidence intervals for the true mean % weight placed on the hind and right limbs were reported, as well as the confidence intervals for the true mean of the center of mass coordinates. Measurements also were averaged by dog and the weight distribution ratios, center of mass coordinates, and confidence intervals for those means also are shown.

	Fore:Hind limb % distribution (± SD)	**Left:Right limb % distribution (± SD)**	**X center of mass coordinate ± SD**	**Y center of mass coordinate ± SD**
Group 1				
All measurements	62.6:37.4 (± 4.4)	52.4:47.6 (± 8.5)	0.38 ± 0.04	0.48 ± 0.07
95% CI (Mean)	37.2 - 38.3	46.6 - 48.6	0.382 – 0.392	0.471 – 0.487
Averaged by Dog	62.3:37.7 (± 3.5)	52.7:47.3 (± 6.2)	0.39 ± 0.03	0.48 ± 0.05
95% CI (Mean)	36.9 - 38.5	45.9 - 48.7	0.379 – 0.394	0.466 – 0.488
Group 2				
All measurements	62.5:37.5 (± 4.7)	52.7:47.3 (± 8.7)	0.38 ± 0.04	0.48 ± 0.07
95% CI (Mean)	36.9 - 38.2	46.1 - 48.6	0.376 – 0.388	0.467 – 0.487
Averaged by Dog	62.5:37.5 (± 3.6)	53.1:46.9 (± 6.6)	0.38 ± 0.03	0.47 ± 0.05
95% CI (Mean)	36.5 - 38.5	45.1 - 48.7	0.374 – 0.393	0.460 – 0.490
Group 3				
All measurements	62.4:37.6 (± 4.9)	52.8:47.2 (± 8.9)	0.38 ± 0.03	0.47 ± 0.05
95% CI (Mean)	36.8 - 38.4	45.8 - 48.7	0.372 – 0.390	0.460 – 0.489
Averaged by Dog	62.4:37.6 (± 4.0)	53.1:46.9 (± 6.8)	0.38 ± 0.04	0.47 ± 0.07
95% CI (Mean)	36.5 - 38.8	45.0 - 48.8	0.375 – 0.389	0.463 – 0.487

Table 2— Data from 54 agility dogs with no previous injuries according to size. The mean weight distribution among pairs of limbs are reported for each measurement (3-5 per dog) as well as the averaged data for each dog. The 95% confidence intervals shown are for the mean of the hind, and right limb % weight distributions and for the mean of the two-dimensional center of mass coordinates. There were 5 small dogs, 31 medium dogs, and 18 large dogs. Dog turned their heads varying degrees to the right or left during some measurements.

	Fore:Hind limb % distribution (± SD)	**Left:Right limb % distribution (± SD)**	**X center of mass coordinate**	**Y center of mass coordinate**
Small (3 - 7 kg)				
All measurements	63.5:36.5 (± 3.2)	51.3:48.7 (± 8.0)	0.38 ± 0.03	0.49 ± 0.07
95% CI (Mean)	34.9 - 38.1	44.7 - 52.7	0.360 - 0.390	0.459 - 0.527
Averaged by Dog	63.6:36.4 (± 3.0)	52.1:47.9 (± 6.9)	0.38 ± 0.03	0.49 ± 0.06
95% CI (Mean)	32.7 - 40.2	39.4 - 56.4	0.341 - 0.410	0.412 - 0.560
Medium (7 - 20 kg)				
All measurements	63.6:36.4 (± 4.6)	53.5:46.5 (± 9.1)	0.37 ± 0.05	0.47 ±0.07
95% CI (Mean)	35.5 - 37.3	44.8 - 48.3	0.364 - 0.382	0.456 - 0.484
Averaged by Dog	63.6:36.4 (± 3.6)	53.7:46.3 (± 6.8)	0.37 ± 0.04	0.47 ± 0.06
95% CI (Mean)	35.0 - 37.7	43.8 - 48.8	0.360 - 0.385	0.447 - 0.488
Large (> 20 kg)				
All measurements	61.0:39.0 (± 3.5)	52.2:47.8 (± 8.2)	0.40 ± 0.03	0.48 ± 0.06
95% CI (Mean)	38.2 - 39.9	45.9 - 49.8	0.389 - 0.406	0.469 - 0.500
Averaged by Dog	60.8:39.2 (± 2.5)	52.5:47.5 (± 6.2)	0.40 ± 0.03	0.48 ± 0.05
95% CI (Mean)	37.9 - 40.4	44.4 - 50.5	0.387 - 0.410	0.458 - 0.506

Discussion

Overall Weight Distribution of Dogs

The average static weight distribution for dogs in the current study was approximately 63% weight on the front limbs, and 37% weight on the hind limbs with near 47% of body weight on the right pair of limbs. The left to right variation was greater than front to back variation, as illustrated by the ellipsoid shape of the bivariate boxplot and confidence intervals on the *x* and *y* axes in **Fig. 2**. This was true for all 3 groups of dogs in the study. The front to back distribution closely agrees with unpublished data presented by Chalayon et al*.* (2013), but our data do not show an equal left to right distribution. Moreover, our data appear to be more variable in the left to right direction. This can be explained by variation of head position in our study. Two-dimensional center of mass measurements for the three groups had similar averages (**Table 1**). According to the two-dimensional center of mass measurements, on average dogs in this study distributed roughly 62% of their weight towards the front and 38% towards the back, with about 48% of weight on the right side. However, as seen when comparing the *y* axis of **Figs. 2 and 3**, center of mass measurements were less variable in left to right distribution.

Previous Injuries and Their Effects on Static Measurements

Some dogs in this study had previous injuries, but did not show any visible signs of lameness during the time of measurements. These dogs, with the exception of one that produced outliers in the data (and was subsequently removed), were included in Group 1 and their measurements are shown in **Figs. 2 and 3** as closed black circles. Measurements from these dogs did not fall outside the boxplot fence and appeared to be evenly distributed among the measurements of non-injured dogs. We could not discern any obvious patterns that set previously injured dogs apart from those with no injuries based on these plots. However, we have determined that either 1) dogs with previous injuries never developed abnormal weight distributions, or 2) they appear to return to a normal and healthy distribution given time. Many of our canine agility competitors (33%) had previous injuries. With such a high prevalence of injured dogs, it would seem that previously injured, but currently healthy dogs should be included in the creation of a database of healthy dogs. These may show slightly more variation in left to right distribution than the non-injured dogs and inclusion of previously injured dogs may create a healthy database that better represents an actual patient population and the variation that may be found with it.

Effects of Horizontal Head Position on Static Measurements

The MANOVA tests we ran on the three groups of dogs to determine whether horizontal head position had an effect on weight distribution raised some questions. Group 1 results showed that head position does affect the measurements of both static weight distribution and two-dimensional center of mass. However, when the previously injured dogs were removed and the MANOVA was conducted on Group 2, the effects of head position were non-significant. Further, when extreme head turns (greater than 45˚) were removed (to leave only Group 3 dogs) the head position was once again significant, though narrowly.

First, the head position had the most significant effect on the measurements of dogs in Group 1, which included dogs with previous injuries. The effects of head position on Groups 2 and 3 were similar and much less significant compared to Group 1. We believe this could be because previous injuries did affect the ability of dogs to maintain their weight distribution while turning their heads. If previously injured dogs are less able to maintain their average weight distribution during head turns we would expect to see the more significant results on Group 1 while those effects are not seen with the same strength on Groups 2 or 3.

Second, the MANOVA results of Groups 2 and 3 showed that head position had a weak effect on these static measurements. We examined the data more closely by dividing them into measurements with particular head positions, and we determined that the measurements most different (in left to right distribution) from each other were slight left and slight right head turns (less than 45˚ from center). Therefore, the inclusion of extreme head turns in Group 2 may have made the significant differences between these two head positions harder to detect. When those extreme head turns are removed in Group 3, the significance between these two head positions becomes more detectable. This is not to say that extreme head turns do not matter, but we believe that during slight head turning, dogs counterweight the rear limb on the opposite side of the head turn. We think that dogs are unable to counterweight when their heads are turned to the extreme right or left, and therefore their weight is distributed more evenly in those cases. The aim of this study, however, was only to determine whether horizontal head position was a factor to consider when creating a database for healthy dogs. We have shown that head position does have a significant effect on measurements, particularly in previously injured dogs. Therefore creation of healthy databases should only include straight head positions during measurements.

Correlation Between Body Weight and Weight Distribution

We used only straight head positions from non-injured dogs to examine the correlation between body weight and the static measurements of front to back, left to right, and the center of mass distribution. Removing the horizontally turned head positions and previously injured dogs allowed us to determine whether body weight alone is correlated with the distribution of weight in a dog. We found that there was a weak correlation between the front to back weight distribution and dog body weight such that larger dogs distribute proportionately more weight to the back limbs. This relationship also held true for the x center of mass coordinate. However, there was no correlation between the left and right weight distribution and the body weight of dogs. With straight head positions, we did not expect any correlation between size and left to right distribution, but we were unsure if body weight would be correlated with distribution of weight from front to back, because we realized that dogs are extremely variable in body type at any given weight.

For example, a Bulldog may weigh 25 kg, but we expect the weight distribution of this dog to be different from a 25 kg Greyhound. Dog body weight can tell us little about the conformation of the dog. However, the weak correlation suggests that the body type of dogs may affect the front to back distribution of weight, but that no matter the conformation, left to right distribution remains relatively equal when the head is kept straight. This data demonstrates that creating a database of healthy data based on size categories (i.e. large, medium, and small dogs) will not be sufficient, and that conformation specific groups of dogs should be used to establish normal data for specific body types.

Static Weight distribution and Two-dimensional Center of Mass Comparison

One objective of the study was to compare static weight distribution to two-dimensional center of mass and determine if one might be more sensitive to detect abnormal measurements from injured dogs. We did find that both measurements were similar in proportion with 63:37% front to back weight distribution and 62:38% distribution of weight from front to back in center of mass measurements. These averages were very similar, however, the two-dimensional center of mass measurements (which take foot position into account) are less variable in left to right distribution. This is illustrated in **Fig. 3** as the shape of the fence is more circular in contrast with the ellipsoid shape of **Fig. 2** (static weight distribution). Only one non-injured dog measurement fell outside the fence in **Fig. 3**. This dog placed more weight on its left side for all three of its measurements and turned its head to the right (less than 45˚). The two-dimensional center of mass detected the difference in one of those measurements with all of the head positions included, while the static weight distribution boxplot could not. This along with the decreased variation in left to right distribution suggests that two-dimensional center of mass may be better able to detect abnormal measurements and orthopedic abnormalities.

In summary, our data agree with the unpublished data by Chalayon et al. (2013) that dogs distribute weight with close to 63% on the front limbs and 37% on the hind limbs. We found that including measurements with horizontal head turns increased variation in the left to right weight distribution, and the dogs in this study with various head turns had an average of 47% of weight on the right limbs. Head position had more significant effects on our Group 1 dogs, suggesting that previously injured dogs are less able to compensate and they changed their weight distribution in response to head turning more than non-injured dogs. While the effects are weakly significant, head position does have an effect on the measurements of weight distribution and a normal database of dog measurements should only include straight head positions, though previously injured dogs can likely be included if pre-screening determines the measurements are not outliers compared with healthy measurements.

Dog body weight was correlated with the front to back distribution of weight such that larger dogs tend to have more weight distributed towards the back. Unfortunately, the body weight tells us little about the conformation of the dog, and radically different body types can often be similar in body weight. This suggested to us that databases need to be created for dogs with certain body types, and not based on size category. These could be breed specific or, to accommodate mixed breeds, they could be based on similar body conformations. We determined that static weight distribution and two-dimensional center of mass measurements were similar in average distribution, but that the center of mass measurements were more conserved during head turns as evidenced by decreased variation in the left to right distribution of weight. This suggests that center of mass may be a more sensitive measurement to use in the bivariate boxplot.

To move forward and apply this data to veterinary practice, databases of static weight distribution and two-dimensional center of mass, specific to certain breeds or dog body types, and measurements with only straight head positions, need to be created to compare injured dogs against. It appears that dogs with previous injuries are common among agility competitors and should be included in the creation of these new databases, providing they don't produce severe outliers in the data set, because of the prevalence of previous injuries (33%) among canine athletes.

FOOTNOTES

a. OHAUS ES Series Digital Bench Scale, Model 71138833, OHAUS Corporation, Parsippany, NJ, USA.

b. ImageJ 1.45s, Version 1.6.0_20, Wayne Rasband, National Institutes of Health, USA, http://imagej.nih.,gov/ij.

c. R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, http://www.R-project.org/.

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CHAPTER 2:

Gait characteristics and heart rate response of healthy dogs during partial-water immersion on a treadmill

ABSTRACT

Objective— Determine temporal-spatial gait characteristics, and heart rates of dogs on a treadmill under dry conditions and during partial-water immersion.

Animals— 12 healthy dogs (variety of breeds and both sexes) with no orthopedic limitations.

Procedures— Gaits of dogs were recorded at 3 increasing speeds, on an underwater treadmill and analyzed using image processing software and multivariate statistics. We determined symmetry between the limbs for gait characteristics. Heart rates were recorded with a non-invasive chest monitor.

Results— At 3.2 km h^{-1}, duty factor and stride frequency decreased, whereas stride length, swing phase duration, and heart rate increased in partial-water immersion versus dry conditions. Stance phase duration was not significantly different between dry and wet conditions. Increasing speed between 1.6 and 6.4 km h^{-1}, depending on the dog, on the dry treadmill increased stride length, and stride frequency, while duty factor and stance phase decreased, and heart rate did not change. Increasing to identical speeds in water had similar effects on gait characteristics, but also raised heart rate. In both dry and partial immersion conditions all variables were symmetrical between limbs at 3.2 km h^{-1}, except for stride frequency.

Conclusions and Clinical Relevance—Heart rate increased during dynamic treadmill exercise in partial-water immersion versus dry conditions for healthy, non-trained dogs. Reference values for temporal-spatial gait variables at increasing speeds may be used to

design and monitor sub-maximal treadmill protocols for hydrotherapy. In particular, duty factor can define gait changes between dogs and exercise conditions. We also demonstrated that non-invasive heart rate measurements can be collected under wet or dry conditions, and may be used to monitor dog fitness and regulate workload intensity.

INTRODUCTION

Gait characteristics provide valuable quantitative measurements defining normal gait patterns, and can identify subtle abnormalities to diagnose orthopedic limitations in dogs (Leach et al., 1977; Beraud et al., 2010; Light et al., 2010; Moreau et al., 2010; Sanchez-Bustinduy et al., 2010; Abdelhadi et al., 2013). Hildebrand (1966 and 1977) was one of the first to examine locomotion of different dog breeds. He illustrated in 1968 that conformation and size difference among breeds of dogs led to variation in preferred gait patterns at various speeds (Hildebrand, 1968). To control for the variation in gait characteristics among breeds, many studies of locomotion in healthy dogs focused on just 1 or 2 specific breeds, such as the greyhound (Bertram et al., 2000), Labrador retriever (Agostinho et al., 2011), and beagle (Piccione et al., 2012). Treadmills have been used to maintain a steady speed during some studies (Decamp et al., 1993; Agostinho et al., 2011; Abdelhadi et al., 2013), and some also included force platforms to measure vertical ground-reaction forces (Kram and Powell, 1989; Levine et al., 2010). Force platforms provided diagnostic data concerning vertical forces exerted on the paws. Although some gains in our fundamental understanding of canine gait have been made over the last 46 years since Hildebrand (1968), we are many years behind the studies of human gait (Colborne, 2007). What is currently lacking are data that establish normal gait characteristics, and that support the use of particular therapeutic options during treatment.

One therapeutic option that has been increasingly used in veterinary clinics is hydrotherapy (Prankel, 2008; Waining et al., 2011). This type of therapy involves either swimming or walking in warm water, and both types of exercise have advantages. These include analgesic effects on pain, and the reduction of weight bearing on the joints during therapy (Prankel, 2008). Hydrotherapy is also used in animals for improving cardiovascular fitness and weight management when arthritic disease is present (Rivière, 2007). While a pool and swimming therapy allow the therapist to be close to the dog, the underwater treadmill option provides the opportunity to watch and record the movements of the dog through the side of the tank (Prankel, 2008). Another advantage of walking on an underwater treadmill is that speed can be accurately regulated and the therapist or researcher therefore has more control over the work intensity of the dog. Dogs walking through water expend more energy because of the increased viscosity and drag of the media (Weigel and Millis, 2014), and we expect their gait characteristics to change accordingly. We also expect, based on studies of heart rate in humans (Evans et al., 1978; Whitley and Schoene, 1987) and horses (Voss et al., 2002; Lindner et al., 2012), that oxygen consumption and energy expenditure will increase in partial-water immersion on a motor-driven treadmill, at a given speed, and therefore increase heart rate in dogs compared with dry conditions. Although several studies of dog heart rates during treadmill exercise have been published (Brouha et al., 1936; Tipton et al., 1974; Sneddon et al., 1989; Smith et al., 2005; Piccione et al., 2012;

Essner et al., 2013), to the best of our knowledge, non-invasive measurements of heart rate, specifically comparing partial-water immersion and dry conditions on a treadmill, have not.

The first objective of this study was to establish normal gait characteristics for healthy dogs moving on a treadmill during partial-water immersion. Our second objective was to measure corresponding heart rates, non-invasively, and determine the effects of partial-water immersion on heart rate responses during treadmill exercise. Although some studies have determined how dogs alter temporal-spatial gait characteristics with increasing speed on a dry treadmill (Maes et al., 2008), our third objective was to determine how dogs increase speed in partial-water immersion, and determine whether increasing speed affects heart rate differently during partial-water immersion versus dry conditions. Our goal was to use treadmill speeds appropriate for a therapeutic setting.

Limb range of motion in dogs increases at particular water levels while walking under partial-water immersion (Levine et al., 2010); consequently, one of our working hypotheses was that basic gait characteristics change when dogs move on a treadmill during partial-water immersion compared with dry conditions. We also predicted that heart rates of dogs would increase more during partial immersion at a given speed, because of the increased resistance to forward motion through water, and that by increasing speed, gait characteristics also would change.

MATERIALS AND METHODS

Dogs— Our subjects included 12 dogs, ranging from 9 months to 12 years old, and weighing 2.6-31.6 kg (17.0 ± 9.3 kg, mean ± SD). Body-condition scores averaged 3.0 ± 0.5 (on a scale of 1 to 5 with 1 being very thin and 5 representing obese). There were 3 intact males, 6 neutered males and 3 spayed females. The dogs had routine physical examinations within 1 year of our study. Owners were questioned concerning the medical history, diet, and exercise routines of their dogs. All dogs were healthy, with no past or current orthopedic injuries or ailments. Dogs were not pre-trained to walk on the treadmill and were not familiar with the equipment, measurement devices, or research personnel. Nonetheless, all of the dogs rapidly adapted to the treadmill and successfully completed the research protocol without showing aggressive behavior, fear, or erratic heart rates while on the treadmill. We selected dogs that represent a variety of sizes and breeds, and would be representative of a real patient community. This study (number 694) was reviewed and approved by the Idaho State University Institutional Animal Care and Use Committee in accordance with the National Research Council Guide for the Care and Use of Laboratory Animals.

Exercise Stimuli and Measurement of Temporal-Spatial Gait Characteristics— We used a custom-made motor-driven (2.5 HP), level (0% grade) treadmill for dogs (belt dimensions: 50.5 cm wide x 152 cm long) that was enclosed in a rectangular Plexiglas tank (244 cm long x 85 cm wide x 115 cm deep) with see-through doors to provide and monitor specific exercise conditions. The “underwater” treadmill was filled to the desired height (up to the elbow of the dog) with thermostatically controlled (30°C) water from nearby reservoirs. It has been estimated that water at elbow height simulates 85% of normal weight bearing (Levine et al., 2002). We chose 30°C because this is a common water temperature used in hydrotherapy for its analgesic effect on joint pain (Prankel, 2008). Dogs and their owners entered the treadmill, and the owner stood in front of the treadmill belt, motivating the dog to walk on the moving treadmill with treats, toys, or verbal rewards. Owners focused on keeping the dogs moving at a steady rate and keeping their attention focused in front so that head position remained neutral (neither up or down, nor left or right). Depending on dog size, and their ability to maintain a uniform gait pattern at a particular speed, each dog walked at 3 increasing speeds. Each dog walked in dry conditions first, followed by partial-water immersion, at identical speeds to those under dry conditions. For comparative purposes, every dog walked at 3.2 km h^{-1}, and two other speeds, determined by the comfort of each dog and its ability to walk in partial immersion at those speeds.

A walking gait was defined as movement where each foot has a separate footfall, and at least two feet were in contact with the ground at all times. Conversely, pacing was defined as movement where both right limbs (front and rear) move at the same time, and have simultaneous footfalls, followed by the left limbs (front and rear), which also share one footfall. A trot occurs when the front left and rear right limbs move in unison with the same footfall, and the right front and left rear feet follow, also in unison.

A high-speed [up to 250 frames per sec (fps)] digital camera[a] was used to record gait characteristics of dogs on the underwater treadmill at 60 fps with standard fluorescent lighting from the ceiling above the treadmill. Our camera was stationary (on a tripod) and positioned 105 cm from the treadmill on the left side of the dog with the aperture 29 cm above the platform. Each recording occurred after 3 min at a particular treadmill speed and consisted of approximately 300 black and white images, or 3 complete gait cycles. For larger dogs, we often recorded separate gait cycles for front and back legs. Data was extracted from videos and analyzed using two types of software[b,c]. This software combination allowed us to review the videos frame by frame, and determine the temporal-spatial dynamics of foot strike (**Fig. 5A and 5D**) and foot lift (**Fig. 5B and 5E**). We measured five variables in each gait cycle: (1) stance phase—the amount of time the foot spends on the ground; (2) swing phase—the amount of time between a foot lift and subsequent foot strike; (3) stride length—how far a particular foot moves from one foot strike to the next; (4) stride frequency—how often a particular foot strike occurs; and (5) duty factor—the percentage of the stride that the foot remains in contact with the ground.

Symmetry ratios for each of the gait characteristics were calculated with the average values of these variables from each limb from each dog. A previous study reported symmetry ratios of Labrador Retrievers who walked across a force platform, and we have reported our symmetry ratios in a similar manner (Light et al., 2010). The symmetry ratios for each dog were tested using t-tests, or Wilcox signed rank tests when the data was not normal to determine if they were significantly different from 1.00. We observed no difference between front and hind limbs, or left versus right limbs (paired *t*-tests), and the symmetry for most variables was not significantly different from 1.00. Therefore, we simplified the data presentation and focused on the left front limb to illustrate changes between conditions and speeds.

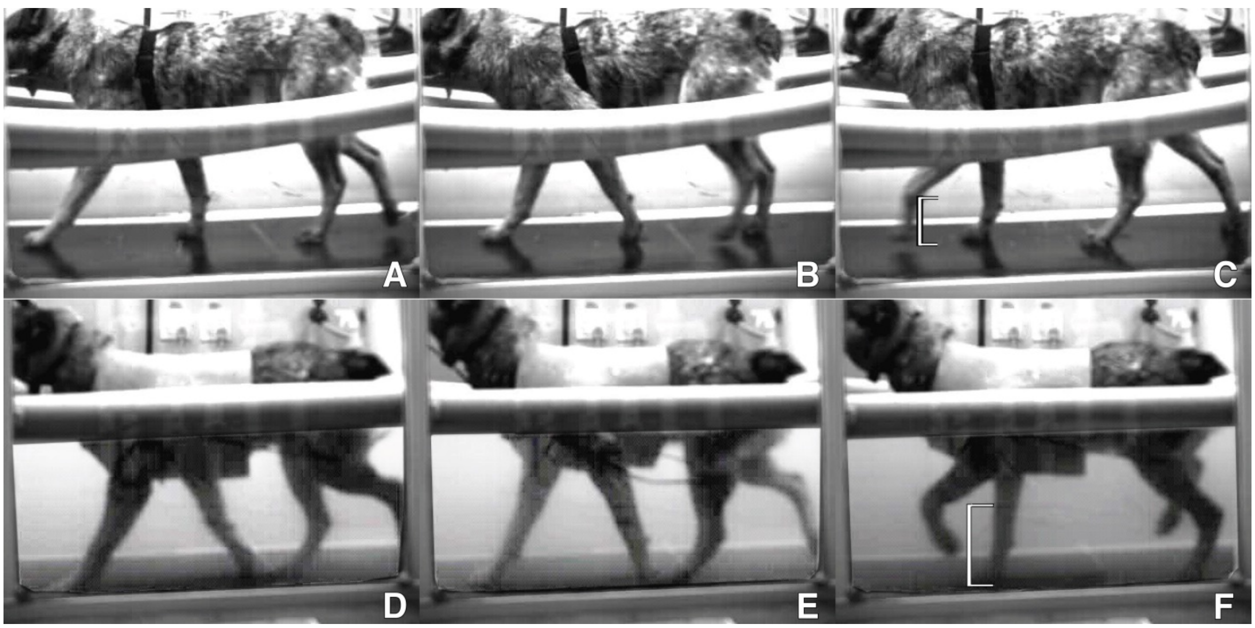

Figure 5— Examples of paw strike (A), paw lift (B) and maximum paw-lift height (C) of the left front foot. Panels A, B and C show one dog at 3.2 km h^{-1} on the dry treadmill, and panels D, E and F illustrate strike, lift, and maximum paw-lift height of the same dog in partial-water immersion at the same speed. Dogs did not always require the wet synthetic towel and custom made vest to get a signal from the heart rate monitoring unit, and in panels A-C the dog is wearing only the heart rate chest transmitter.

Non-Invasive Measurement of Heart Rate— Each dog was fitted with: (1) an appropriately sized heart-rate monitor chest strap and wireless chest transmitter[d] with a generous amount of electrode cream[e] applied to the transmitter to promote conductivity; (2) a moist synthetic chamois; and (3) a custom neoprene vest around the towel, chest strap and transmitter to maintain effective position and moisture of the sensor. Unlike previous studies where the coats of dogs were either clipped (Essner et al., 2013) or shaved (Tipton et al., 1974), we were able to record average heart rates from all of our experimental animals, in dry or wet conditions, without altering the coat. In some circumstances the wet chamois and vest were not necessary to obtain a signal from the chest transmitter, and the dog was only outfitted with the chest strap and transmitter (**Fig. 5A-C**). Pre-exercise heart rate was obtained while the dog was standing, just before introduction to the underwater treadmill. Wrist units[g] were used to receive and display heart rate measurements. The heart rate monitoring system displayed an averaged measurement every 5 seconds and did not display instantaneous measurement of heart rate. The heart rate monitoring system we used is accurate in humans up to 199 bpm, but dogs can easily exceed that value during moderate intensity treadmill exercise (Tipton et al., 1974; Rovira et al., 2008). Given potential limitations of measuring heart rates above 180 bpm, we opted to exercise dogs at conservative submaximal speeds (between 1.6 and 6.4 km h^{-1}) that are likely utilized in a rehabilitative setting.

At each speed, heart rate was recorded every 15 sec for 3 min, starting after the dog had walked at that speed for 2-4 min (*n* = 8-16 measurements). This process was repeated for each progressive speed (**Fig. 6**). Once measurements on the dry treadmill were completed, the dog was given water ad libitum and allowed to rest for 10 min before identical measurements were recorded with water in the treadmill. Our choice of the 10 min recovery time was based upon heart-rate recovery of just 9 min for non-trained dogs after a higher intensity treadmill test (Tipton et al., 1974).

Statistical Methods— To assess potential differences between limbs, we first calculated symmetry ratios and conducted paired *t*-tests of temporal-spatial gait variables recorded from the 4 limbs. We conducted a principal components analysis (PCA)[h] on our temporal-spatial gait variables from the left front limb at 3.2 km h^{-1} to determine which variable(s) distinguish the two experimental conditions (partial-water immersion and dry conditions). We then completed analysis of variance (ANOVA)[h] tests on the mean values for each temporal-spatial gait variable. Some temporal-spatial gait characteristics had non-normal distributions, and the Friedman's rank sum test, a non-parametric analog of a randomized block ANOVA[h], was used on those variables. Additional ANOVA[h] tests were conducted on the remaining three limbs to determine whether temporal-spatial gait variables change consistently across limbs. We also performed a mixed-model repeated measures analysis[i] (with dog and time as random effects) on heart rate at 3.2 km h^{-1} to determine differences between dry and partial-water immersion, and to assess whether there were time effects across the repeated measures. Finally, we conducted an analysis of covariance (ANCOVA)[h], with time as the concomitant variable, on each gait variable, and on heart rates of dogs in dry and partial-water immersion conditions separately, to determine which of those characteristics changed with increasing speed. Statistical significance was set at $P < 0.05$ for all tests.

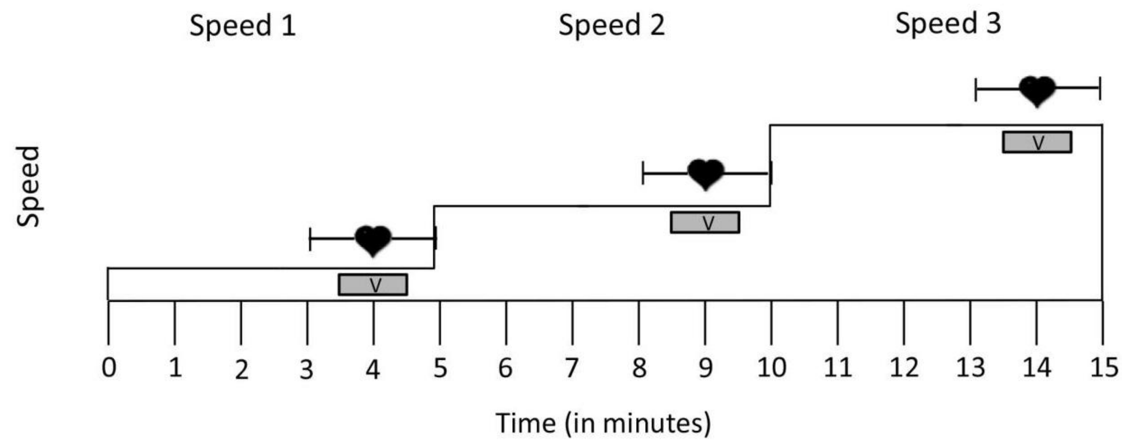

Figure 6— The sequence of events for recording heart rate and video while dogs walk on a treadmill is shown here in stages. Dogs were outfitted with the heart rate monitor and then led into the treadmill by their owners. The treadmill speeds varied depending on the size of the dog, and at what speeds they could comfortably walk. Every dog walked at 3.2 km h^{-1}. Smaller dogs walked at 1.6, 2.4, and 3.2 km h^{-1}; medium sized dogs walked at 1.6, 3.2, and 4.8 km h^{-1}; and large dogs walked at 3.2, 4.8, and 6.4 km h^{-1}. The dogs were allowed to walk for at least 3 min on the treadmill at a particular speed, so that their heart rates reached a steady state and their gait patterns became regular. After 3 min of walking, heart rates were recorded every 15 sec using a heart rate monitor, and the videos of gait were taken between 3 and 5 min of the dog walking at a particular speed. Videos of three gait cycles, lasting only a few sec, were recorded at 60 Hz. Once data for that speed was collected, the treadmill speed was increased slowly (over 10 sec) to the next speed. The process was then repeated for speeds 2 and 3. At that time, dogs were allowed to stop and rest while water was pumped into the treadmill system to the appropriate height. After 10 min, when the heart rates of our dogs had reached a steady state, we began the same process over again with water in the treadmill at the same speeds.

RESULTS

The PCA of gait characteristics revealed duty factor, stride length, and swing phase as the most important variables in separating dogs in dry versus partial-water immersion conditions. In the eigenanalysis, 87.0% of the variation among dogs in spatial gait space was explained in the first two principal components. The dry and partial immersion data were separated in gait space and the three smallest dogs, in both dry and partial-water immersion conditions, were separated in these dimensions into their own group.

Stance phase of the left front limb did not differ significantly when dogs walked in partial-water immersion, compared with dry conditions at 3.2 km h^{-1}; however, swing phase, stride length, and heart rate increased in partial-water immersion, whereas duty factor and stride frequency decreased (**Table 3**). The duty factor of our 3 small dogs (mean ± SD, 0.52 ± 0.03) was smaller than that of our 9 large dogs (0.64 ± 0.03) in dry conditions and both groups decreased duty factor in partial-water immersion (small dogs, 0.36 ± 0.08; large dogs, 0.52 ± 0.03).

Averaged symmetry ratios (**Tables 4 and 5**) were not significantly different from 1.00 except for the stride frequency variable in both dry and partial immersion conditions. Stride frequency was not symmetrical between forelimbs and hind limbs.

Overall, partial-water immersion resulted in higher heart rates than dry conditions (**Fig. 7**). Mean heart rates of the dogs at 3.2 km h^{-1} increased significantly in partial-water immersion; however, one dog (#5) exhibited a slight (3.4%, 6.4 bpm) decrease in heart rate in partial-water immersion and another (#10) had no significant change in heart rate between the two study conditions (2.7% increase, 3.8 bpm). At 3.2 km h^{-1} in dry conditions, average heart rates for individual dogs ranged from 104-188 bpm. During partial water immersion at the same speed heart rates ranged from 130-193 bpm. Across all speeds, heart rates were between 104 and 189 bpm during dry conditions and 123 and 217 bpm with partial water immersion. The resting heart rate of 4 of our dogs while waiting to enter the treadmill was 120 ± 17.

Results from ANCOVAs indicate that stance phase and duty factor decreased as dogs walked faster, whereas stride length, and stride frequency increased. Increasing speed on a dry treadmill, between 1.6 and 6.4 km h^{-1}, did not change swing phase duration or heart rate (**Table 6**). Conversely, moving faster during partial-water immersion decreased stance phase, swing phase, and duty factor, whereas stride length, stride frequency, and heart rate all increased (**Table 7**). It is noteworthy that several dogs (*n* = 5) switched from a walking gait on the dry treadmill to a trot or a pace during partial-water immersion at that speed.

Table 3— Temporal-spatial gait variables of the left front limbs*, heart rate values, and ANOVA statistics for dry versus partial-water immersion treadmill trials. Percent change reflects the data for partial-water immersion divided by dry conditions. Values are Mean ± 1 SD. *P*-values and test statistics concern the null hypothesis of no effects of partial-water immersion. Data reported from 12 healthy dogs walking at 3.2 km h^{-1} on the dry treadmill and in partial-water immersion. Four dogs changed their gait to a trot and 1 dog changed to a pace during water immersion.

Variable	**Dry Treadmill**	**Partial-water Immersion**	**Percent Change**	***F*-Value, or χ^2 Value†**	***P*-Value**
Stance Phase† (sec)	0.45 ± 0.16	0.47 ± 0.16	+2.9%	$\chi 12=0.40$	0.5271
Swing Phase (sec)	0.27 ± 0.05	0.47 ± 0.05	+74.5%	$F_{1,11} = 188.5$	< 0.0001
Stride Length (m)	0.65 ± 0.18	0.84 ± 0.18	+29.3%	$F_{1,11} = 94.1$	< 0.0001
Stride Frequency (sec^{-1})	1.54 ± 0.62	1.13 ± 0.29	-26.8%	$F_{1,11} = 17.1$	0.002
Duty Factor† (%)	61.1 ± 6.0	48.3 ± 9.0	-21.0%	$\chi 12=12.0$	< 0.0001
Heart Rate (bpm)	145 ± 25	166 ± 22	+14.4%	$F_{1,11} = 7.9$	0.0104

*Temporal-spatial characteristics were measured on the left hind limbs but a paired t-test showed no significant difference between the left front and left hind feet and ANOVA results were similar between dry and partial-water immersion conditions for the left hind limb.

†Due to presence of outliers, Friedman's rank sum test for randomized block designs was used for stance phase and duty factor. The Friedman's test statistic has the distribution $\chi 12$ under H_0.

Table 4— Symmetry ratios for 5 temporal spatial gait variables measured in 12 healthy dogs walking on a dry treadmill at 3.2 km^{-hr}.

Variable	Front:Back	Left:Right	LF:RF	LH:RH	LF:LH	RF:RH
Stance Phase	1.044 ± 0.132	0.929 ± 0.27	0.965 ± .111	0.983 ± 0.075	1.038 ± 0.177	1.052 ± 0.132
Swing Phase	0.948 ± 0.151	0.978 ± 0.118	0.973 ± 0.085	1.038 ± 0.140	0.921 ± 0.157	0.983 ± 0.184
Stride Length	0.986 ± 0.107	1.014 ± 0.349	0.995 ± 0.067	1.003 ± 0.057	0.980 ± 0.101	0.994 ± 0.131
Stride Frequency	1.140 ± 0.095*	1.351 ± 0.492	1.035 ± 0.068	1.299 ± 0.090*	1.028 ± 0.109	1.288 ± 0.107*
Duty Factor	1.039 ± 0.098	1.073 ± 0.344	1.000 ± 0.055	0.979 ± 0.078	1.052 ± 0.107	1.029 ± 0.111

*Ratios are significantly different from 1 using a t-test (or Wilcoxon signed rank test if the data failed the Shapiro Wilks normal distribution test)

Table 5— Symmetry ratios for 5 temporal-spatial gait variables measured in 12 healthy dogs partially immersed up to the elbow in an underwater treadmill system at 3.2 km^{-hr}.

Variable	Front:Back	Left:Right	LF:RF	LH:RH	LF:LH	RF:RH
Stance Phase	1.011 ± 0.267	1.034 ± 0.118	1.042 ± 0.072	1.028 ± 0.090	1.019 ± 0.263	1.006 ± .281
Swing Phase	1.057 ± 0.223	1.035 ± 0.356	0.999 ± 0.089	1.022 ± 0.156	1.063 ± 0.297	1.095 ± 0.262
Stride Length	1.022 ± 0.131	1.089 ± 0.415	1.017 ± 0.054	1.094 ± 0.245	0.996 ± 0.112	1.070 ± 0.254
Stride Frequency	1.161 ± 0.133*	1.325 ± 0.667*	0.984 ± 0.036	1.323 ± 0.196*	1.018 ± 0.110	1.366 ± 0.218*
Duty Factor	0.987 ± 0.227	1.049 ± 0.302	1.076 ± 0.167	0.993 ± 0.090	1.020 ± 0.219	0.959 ± 0.255

*Ratios are significantly different from 1 using a t-test (or Wilcoxon signed rank test if the data failed the Shapiro Wilks normal distribution test)

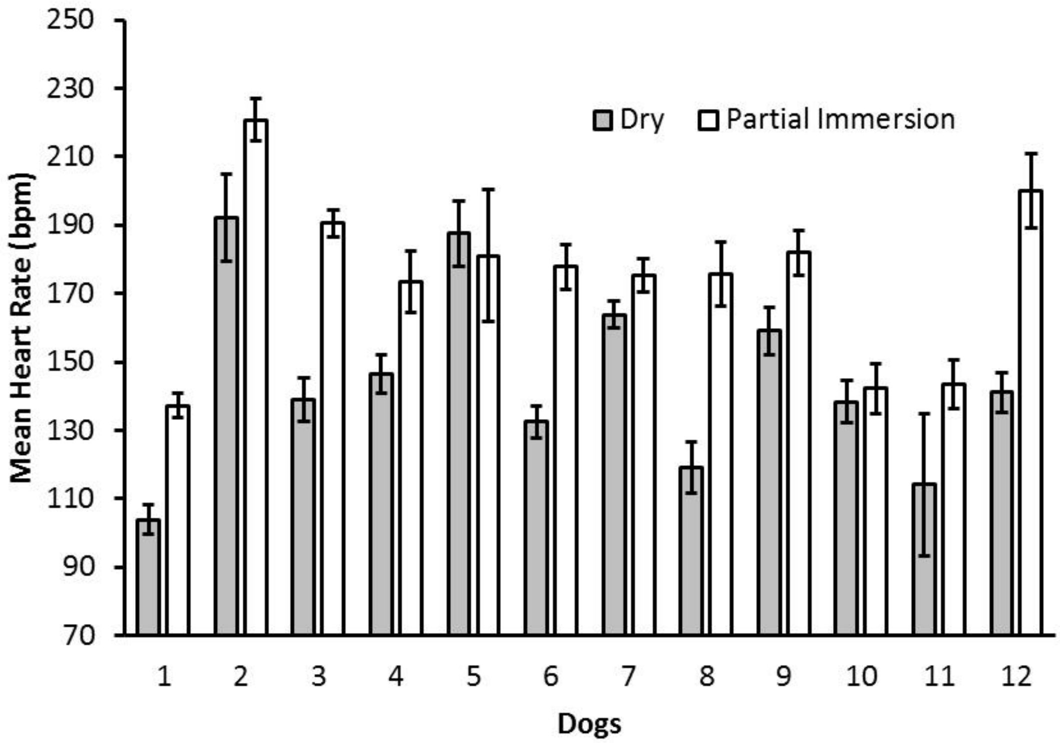

Figure 7— Mean heart rate (± 1 SD) of 12 healthy dogs walking on a treadmill at 3.2 km/h in dry (gray bars) and partial-water immersion (white bars) conditions. Water immersion was at the level of the elbow for each dog. Heart rate was recorded 2 to 3 min after acclimation to the speed of the treadmill and a steady heart rate was achieved.

Table 6— Temporal-spatial gait variables from the left front limbs and heart rate responses to increasing speed on the dry treadmill of 12 healthy dogs. *P*-values and test statistics concern the null hypothesis of no water immersion effect.

Variable on the Dry Treadmill	***F*-Value**	***P*-Value**	**Change**
Stance Phase*	$F_{1,11} = 247.4$	< 0.0001	↓
Swing Phase	$F_{1,11} = 0.54$	0.4704	NS
Stride Length	$F_{1,11} = 529.0$	< 0.0001	↑
Stride Frequency	$F_{1,11} = 95.5$	< 0.0001	↑
Duty Factor	$F_{1,11} = 153.8$	< 0.0001	↓
Heart Rate	$F_{1,11} = 4.0$	0.055	NS

Speeds ranged from 1.6 km h^{-1} to 6.4 km h^{-1} and most dogs walked at 3 different speeds. The change column represents an overall increase (↑), decrease (↓), or non-significance (NS) of that variable as speed increases.
*Due to non-normal distribution of data, stance phase values were log transformed

Table 7— Temporal-spatial gait variables and heart rate responses of 12 healthy dogs to increasing speed in partial-water immersion on a treadmill. *P*-values and test statistics concern the null hypothesis of no water immersion effect. Speeds ranged from 1.6 km h^{-1} to 6.4 km h^{-1} and most dogs walked at 3 different speeds. The change column represents an overall increase, decrease or non-significance (NS) of that variable as speed increases. Two dogs had unusual values for heart rate, resulting in some observation deletions and the exclusion of one dog from the analysis.

Variable	***F*-Value**	***P*-Value**	**Change**
Stance Phase	$F_{1,11} = 185.1$	< 0.0001	↓
Swing Phase	$F_{1,11} = 21.5$	< 0.0001	↓
Stride Length *	$F_{1,11} = 253.3$	< 0.0001	↑
Stride Frequency	$F_{1,11} = 144.8$	< 0.0001	↑
Duty Factor	$F_{1,11} = 83.6$	< 0.0001	↓
Heart Rate†	$F_{1,10} = 111.5$	< 0.0001	↑

*Due to issues with normality, stride length values were log transformed.
† The largest dog in this data set had unusually high heart rates and his data was removed. One unusually high observation from a smaller dog at 1.6 km h^{-1} was also removed from the analysis. Therefore, this ANCOVA included 11 dogs.

DISCUSSION

With increasing use of various exercise stimuli in veterinary medicine for rehabilitation and conditioning, it is essential for veterinarians to understand “normal” gait characteristics, recognize abnormalities and changes due to various treatment modalities, and potentially use heart rate as a measure of work intensity. The purpose of the present study was to define and compare clinically-relevant gait characteristics and heart rate responses of dogs on a treadmill under dry conditions, and during partial-water immersion. The results provide quantitative evidence for an altered gait pattern, and increased cardiovascular exertion during moderate exercise in water.

Effects of Partial-water Immersion on Temporal-spatial Gait Characteristics— Movement of healthy dogs on an underwater treadmill during partial-water immersion increased stride length and the duration of swing phase relative to dry conditions. Conversely, stride frequency and duty factor decreased in water. This agrees with a study of horses where stride frequency decreased, and stride length increased when moving through water (Scott et al., 2010). Dogs slow down their gait cycle in water because of the increased resistance against forward movement. Whether increasing stride length and swing phase, and decreasing stride frequency and duty factor, provide therapeutic benefits in water is beyond the scope of the present investigation. The increase in buoyancy during partial-water immersion, along with the reported changes in gait characteristics, supports the notion that water reduced loading of limbs. In dogs, clinically-relevant conditions also change gait characteristics in the absence of water. Cranial cruciate ligament rupture results in shorter stride length, decreased paw velocity, and the injured limbs show reduced range of motion in the stifle joint (Sanchez-Bustinduy et al., 2010). Lameness of either a front or hind limb will result in decreased stance phase duration for the injured limb (Leach et al., 1977). With a relatively high incidence of orthopedic conditions, and the potential benefits of partial-water immersion, it would be insightful for clinicians to track gait changes during patient rehabilitation.

In the current study, several (5 of 12) dogs did not maintain a walking gait during partial-water immersion. Most of these dogs (n = 4) went from a walk to a trot, whereas another dog paced in water. Therefore, we cannot conclude that the increased physical demand of moving through water, alone, altered the gait characteristics. Regardless of whether dogs changed gait patterns, stride length, swing phase, stride frequency and duty factor changed in partial-water immersion. Changing gait patterns in response to movement through water also has been observed in humans (Hall et al., 1998).

Dog size appears to be an important determinant of gait characteristics and the responses to partial-water immersion in healthy dogs. For example, the PCA of temporal-spatial gait characteristics indicated a separation of the smallest dogs (n = 3) from the larger dogs in trait space, based in large part on duty factor. A previous study by Biewener (1983) on just 4 dogs supports our conclusion that duty factors of large (> 13 kg) and small (≤ 13 kg) dogs differed, with higher values seen in larger dogs at identical speeds. Our analyses also indicated that duty factor remains lower for small dogs during partial-water immersion, indicating that shorter legs reduce the proportion of the stride that the foot remains in contact with the ground, independent of the surrounding media (air or water). Future studies should explore the option that some dogs — depending on size, water height, speed, and conformation — may sacrifice biomechanical efficiency during partial-water immersion and exhibit asymmetrical gaits. Size differences also should be considered as temporal-spatial gait characteristics cannot be directly compared between large and small dogs, although relative changes between conditions can be consistent across different dogs.

Although we did not detect statistical differences between left and right limbs, or front and back limbs for our diverse group of healthy dogs via paired t-tests, a previous study on Labrador retrievers shows that the front limbs and back limbs of dogs lack symmetry (Light et al., 2010) in stance phase and duty factor at speeds between 2.1 and 3.2 km^{-h}. Our symmetry ratios (**Tables 4 and 5**) did not detect asymmetry between limbs at 3.2 km^{-h}, with the exception of stride frequency. Unlike the study by Light and colleagues (2010), our study included small dogs and a variety of dog sizes.

We found that, among the five gait variables measured for our diverse group, only stride frequency symmetry ratios were significantly different from 1.00 ($p > 0.05$). We also recognize, however, that many orthopedic conditions and injuries occur in the limbs, which may cause limb asymmetry, and future studies involving veterinary rehabilitation should address interlimb symmetry when analyzing gait characteristics.

Heart Rate Responses— Resting heart rate in dogs appears to be quite variable, with one study noting averages of 87 bpm and a wide standard deviation of ± 22 bpm for 97 dogs (Haskins et al., 2005). Our dogs likely had increased heart rates (120 ± 17 bpm) prior to exercise because of the new setting and use of unfamiliar equipment. Even after a period of training (time interval not specified) to run on a motor-driven treadmill, Miura and colleagues (1992) reported an average heart rate of 123 ± 15 bpm for 8 instrumented dogs at rest, standing on a treadmill waiting to run. These observations indicate that heart rate of dogs using a treadmill, trained or untrained, will be increased to some degree, because of the anticipation for exercise, or stress associated with exposure to a new environment and equipment.

With the onset of exercise, cardiovascular reflexes are expected, including higher cardiac output and heart rates as exercise intensity and workload increase. The heart rate of 10 of the 12 dogs studied significantly increased during treadmill exercise in partial-water immersion compared with dry conditions. This result likely reflects the increased drag forces and resistance of water to forward movement the dogs encountered during underwater treadmill activity. Such heart rate increases when moving at similar speeds in water versus dry treadmill exercise have been reported in humans between 2.6 to 3.3 km h^{-1} (Whitley and Schoene, 1987), but heart rate does not increase in horses walking at 5.6 km h^{-1} (Voss et al., 2002).

One would also expect that increasing dry treadmill speed should increase heart rate during walking; however, the chosen range of speeds (1.6 to 6.4 km h^{-1}, depending on the dog) and 0% grade represented relatively low-intensity exercise for these healthy dogs. These data are consistent with a previous study by Tipton et al. (1974), wherein healthy, non-trained dogs (*n* = 41) did not increase their heart rates on a level treadmill between 4.8 and 6.4 km h^{-1} during submaximal exercise tests. Our justification for the narrow range of treadmill speeds and a lack of grade was two-fold. First, our goal was to measure exercise responses under clinically-relevant conditions appropriate for hydrotherapy sessions on an underwater treadmill. Second, we recognized the upper limit of the heart rate monitor for humans (200 bpm) was much lower than maximum heart rates of healthy dogs exercising on treadmills (~250 bpm) (Tipton et al., 1974; Melbin et al., 1982) and we therefore restricted treadmill speed and kept it within a narrow range to elicit only a walking gait. Essner and colleagues (2013) validated the use of a similar heart rate monitor on dogs up to 180 bpm, therefore supporting the use of this device for mild to moderate exercise in healthy dogs. It is noteworthy that a combination of regular exercise and weight loss decreased heart rates in obese dogs after 6 weeks (Bouthegourd et al., 2009). Tipton et al. (1974) also demonstrated that trained dogs exhibited lower heart rates than non-trained dogs and showed higher heart rates after 4-5 weeks of deconditioning than when they had completed their training program. As a result, body weight and fitness should be taken into account when measuring heart rate to assess work intensity in dogs. Nonetheless, use of a non-invasive heart rate monitor for veterinary rehabilitation appears to be a valid tool for assessing work intensity and conditioning over a relevant range of heart rates.

Changes in Temporal-spatial Gait Characteristics with Increasing Speed— To increase walking speed on a dry, level treadmill, dogs decreased the time their paws spent on the ground (stance phase), which also resulted in a decrease of duty factor. Conversely, dogs did not change the length of time their paws spent in the air (swing phase), but they did increase their stride length, and stride frequency as they moved faster. These data agree with previous research on dogs increasing speed on a dry treadmill (Maes et al., 2008) and provide an important baseline to understand similar movements in water. In contrast to walking on a dry treadmill, increasing speed during partial-water immersion changed every variable that we measured. Stance phase and swing phase decreased, which also caused duty factor to decrease. With less time spent per stride, stride frequency increased. The buoyant effects of the water allowed for the increase in stride length, and dogs were able to stretch their paws out farther to cover more distance at each increasing speed. The increased stride length was not surprising, since we quickly noticed that dogs tend to lift their paws up much higher when walking in partial-water immersion conditions (**Figs. 5C and 5F**). Overall, these results were similar to the dry treadmill at identical speeds, with the exception of the decreased swing phase and increased heart rate responses in partial-water immersion.

In summary, we have reported comparative values for temporal-spatial gait characteristics and heart rate of healthy dogs during exercise in dry and partial-water immersion conditions on a treadmill. We reported symmetry ratios for each variable in both dry and partial-water immersion conditions to show that gait variables tend to be symmetrical with the exception of stride frequency. We provided evidence of similar mechanisms to increase speed in dry versus partial-water immersion conditions. Development of a simplified program that automates the analysis of video and provides clinically-meaningful data would be valuable. In addition, use of a non-invasive heart rate monitoring system is quite simple and should prove valuable for clinicians wanting to monitor dogs more closely during exercise sessions in water or on dry land.

FOOTNOTES

a. Fastec Imaging, Troubleshooter 250, San Diego, CA, USA.

b. VirtualDub, Version 1.10.2, Avery Lee, http://www.virtualdub.org/.

c. ImageJ 1.45s, Version 1.6.0_20, Wayne Rasband, National Institutes of Health, USA, http://imagej.nih.,gov/ij.

d. Polar, Model T31 N2965, Polar Electro Inc., Lake Success, NY, USA.

e. Buh-bump, Paceline Products Inc., Royal St. Pleasant Valley, MO, USA.

f. Chamois Absorber, Clean Tools Inc., Westmont, IL, USA.

g. Polar, Models F6 and F7, Polar Electro Inc., Lake Success, NY, USA.

h. R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, http://www.R-project.org/.

i. SAS, Version 9.3; SAS Institute, Cary, NC, USA.

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SUMMARY AND CONCLUSIONS

In Chapter 1 we examined possible factors that may affect the static weight distribution and two-dimensional center of mass of agility dogs. We knew from previous force platform studies that dogs of different breeds exhibited different forces on their limbs as they moved (Bertram et al., 2000; Voss et al., 2011). We also knew that certain conditions, such as cranial cruciate ligament tears (Budsberg et al., 1988; Conzemius et al., 2005) and osteoarthritis (Kennedy et al., 2003), produce measureable changes in these same forces. The recent unpublished study by Chalayon and colleagues (2013) provided evidence that lame dogs exhibit differences in their static weight distribution compared to healthy dogs. Finally, a similar study by Pastell and colleagues (2010) showed that in dairy cattle, lameness can be detected by measuring static weight distribution. With all this information in mind, we examined the effects of head position and body size on the static weight distribution and two-dimensional center of mass of a diverse group of agility dogs. Many of these dogs had previous injuries, so we took that opportunity to glean information from those dogs separately. We also compared the static weight distribution measurements with two-dimensional center of mass to determine similarities between the measurements and determine whether center of mass measurements were less resistant to changes from head turning.

Thirty three percent of dogs in this study had previous injuries. We labeled these dogs previously injured and plotted them with non-injured dogs in **Figs. 2 and 3** to observe any obvious patterns. In agreement with our original hypothesis, all of the previously injured dog measurements were inside the boxplot fences for both weight distribution and center of mass. This suggests that — despite previous injuries — many of these dogs had either 1) always maintained a normal weight distribution or 2) returned to a normal weight distribution following an injury. Therefore, many dogs that have been injured in the past could still be classified as healthy animals in future studies.

Consistent with our original hypothesis, we found that head position does affect static weight distribution and two-dimensional center of mass. The effect was more significant in Group 1 dogs which included previously injured dogs. This suggests that previously injured dogs are unable to compensate as well for head turning compared with non-injured dogs. This is supported by the weak effect of head position on Group 2 and 3 dogs which were non-injured. We also determined that the slight horizontal head turns (less than 45˚ from center) were the most divergent from each other in mean and confidence interval (in the left to right distribution only). This explains why the effect of head position was more easily detectable in Group 3 because the extreme head turns included in Group 2 were removed. It is clear however, that head position does affect both of these static measurements and that future studies should only use measurements that include dogs with straight heads.

Body weight of the agility dogs was correlated with the front to back distribution of weight, but not with the left to right distribution. This suggests that the different body types of dogs may affect the front to back weight distribution, but independent of body type, dogs should maintain roughly equal left to right distribution. Because of the very weak correlation, we determined that creating size category databases would not be sufficient to separate out body type effects and that breed specific databases, or at least databases created from dogs with similar body conformation, should be created to minimize the variations in a database in order to more efficiently detect abnormal measurements.

In agreement with our initial hypothesis, normalized two-dimensional center of mass measurements and static weight distribution measurements had similar averages, but center of mass measurements were less variable in the left to right distribution because they incorporated foot position. This results in a variable (center of mass (x,y) measurement) which is more resistant to changes brought on by head position. This was clearly evident from the shape of the center of mass boxplot in Fig. 3 which was more circular with less spread along the Y axis than the static weight distribution boxplot in Fig. 2. Because center of mass is more resistant to changes, we believe it may be a more sensitive way to detect abnormal measurements compared with the static weight distribution measurements.

In Chapter 2 we examined the effect of partial-water immersion, similar to hydrotherapy, using an underwater treadmill system. We wanted to determine whether water alters gait characteristics and heart rates of 12 healthy dogs. We used very slow walking speeds and compared gait characteristics and heart rate as dogs walked dry and partially immersed in an underwater treadmill. All dogs completed measurements at

3.2 km^{-h} and we compared their average gait characteristics and heart rates (**Table 3**). Consistent with our original hypotheses, we found that 4 of 5 gait variables changed significantly when dogs walked in partial-water immersion. Only stance phase showed no significant change. Swing phase, stride length, and heart rate all increased in partial immersion, compared with dry walking. Conversely, stride frequency and duty factor decreased in partial immersion. This made intuitive sense. If swing phase increased, the feet spent more time moving through the water, and the treadmill (which is moving at the same speed) traveled more distance before the feet were put down again, leading to increased stride length. Because dogs took longer to complete a stride, the stride frequency was decreased. Since swing phase increased while stance phase stayed the same the duty factor decreased overall. Heart rates were higher in partial immersion, we believe, because the dogs were facing increased resistance to movement by the viscous water media. This data agreed with our initial hypotheses.

Since our dogs also walked at 3 different speeds we reported the effects of increasing speed on gait characteristics and heart rate, in both dry (**Table 6**) and partial immersion conditions (**Table 7**). In dry conditions our results were consistent with our hypothesis and agreed with a previous study by Maes and colleagues (2008), showing that stride length, and stride frequency increase when dogs move faster, and stance phase and duty factor decrease. Swing phase did not change when increasing speed at these walking speeds and heart rate did not increase over our narrow range of walking speeds either. However, when we examined increasing speeds in partial immersion we found that all our measured variables changed. This also agreed with our original hypothesis that changes in gait characteristics and heart rate with increasing speed might be more pronounced in the water. Stride length, stride frequency and heart rate all increased significantly over increasing speeds, while stance and swing phase and duty factor all decreased. It makes sense to increase stride length and frequency to move faster, and as the frequency of strides increases, the feet have less time to spend on the ground or in the air during a given stride. As a result, duty factor will decrease if a foot spends less time on the ground in proportion to the overall stride time. It was interesting that over our narrow range of speeds heart rate remained unchanged on the dry treadmill, but it increased significantly with increasing speed during partial-immersion at identical speeds. This demonstrates that the workload and energy expenditure of a dog moving through water is increased, and this is measureable through heart rate.

In summary, the information provided from Chapter 1 of this thesis helps set the stage for using static weight distribution to detect and monitor the recovery of dogs from conditions causing lameness or other orthopedic conditions. It has been determined that previously injured dogs are common among canine athletes (33%), and that measurements from these dogs fall within the boxplots including non-injured dogs; previous injuries should not exclude a dog from a healthy database of dog measurements. Future studies creating healthy databases should only allow measurements with straight head positions, especially where previously injured dogs are. Breed specific databases or those which include dogs of similar body conformations should be created for use by clinicians. Two-dimensional center of mass is more resistant to minor changes during static measurement and a bivariate boxplot including center of mass measurements may be better able to detect abnormal measurements than a boxplot of simple static weight distribution. However, another study is required to determine whether the bivariate boxplot fence is sensitive enough to detect abnormal measurements from injured dogs. Information from Chapter 2 has illuminated the effects of partial-immersion in an underwater treadmill on both gait characteristics and heart rate of healthy dogs. This information provides a better understanding of how partial immersion affects the gait of dogs, and provides evidence that partial immersion may be useful in maintaining heart rate conditioning of dogs as well. These two studies will help further research into how we can improve the detection, quantification, monitoring, and treatment of conditions causing lameness.

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