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Nine-axis inertial measurement unit output discriminates activities of varying intensity in the dog

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OBJECTIVE
To explore relationships between 9-axis inertial measurement unit (IMU) output and activities of varying intensity in dogs of various sizes.

ANIMALS
20 healthy, agility course–trained dogs of various ages and sizes.

PROCEDURES
Height, weight, body condition score, age, length from IMU to the ischium, and height of IMU to the floor were recorded. Dogs performed a series of activities (rest, walk, trot, and agility course) while wearing the IMU device. IMU and video output were reviewed by independent investigators. Correlations and multiple regression models were used to explore relationships between independent variables and IMU output.

RESULTS
Calibration demonstrated excellent correlation and concordance between IMUs (intraclass correlation > 0.9) and that the IMUs reliably measured a known acceleration (gravity at rest). Resultant vector magnitude {sqrt[(x^2) + (y^2) + (z^2)]} normalized to body size was calculated from the data. IMU output clearly discriminates between activities of varying intensity in the dog.

CLINICAL RELEVANCE
The inability to accurately measure chronic pain is a barrier to the development of new, or critical evaluation of, therapeutics. Activity monitors (AM) may be the ideal diagnostic target since they are small and provide objective data that can be collected while the pet remains in its natural environment. These results demonstrate the concurrent and predictive validity of the IMU tested. Our long-range goal is to validate an open-source algorithm for the IMU so activity in a pet's natural environment can be used as an outcome measure in future studies.

To improve the diagnosis and treatment of chronic conditions in companion animals, such as pain, obesity, and cardiovascular disease, the veterinary field must address the lack of validated objective measurement modalities that assess pets in their natural environment. An inability to reliably measure disease burden (initial or change) in pets affects the diagnosis of disease and the development of new therapeutics. For example, a primary outcome measure currently used in regulatory, pivotal clinical trials for the study of chronic pain in dogs has been an owner survey.[1–4] Clinical metrology instruments can be useful but are limited by their subjective nature, inherent caregiver placebo effect[5], not directly measuring a change in the patient, and high variation restricting use to large group sizes.[6,7] Additional assessments have included veterinarian examinations and force platform gait analysis; however, these are either subjective or evaluate the pet for a small period of time outside of their natural environment, respectively. Limitations assessing companion animals with chronic pain also handicap our opportunity to utilize them as large animal, spontaneous chronic pain models as a translational model for people, a problem with an economic impact of $600 billion annually.[7,8]

Accelerometers are often used as activity monitors (AMs) and are a component of an inertial measurement unit (IMU). They may be the ideal diagnostic tool since they are small, minimally invasive, mobile, and provide objective data that can be collected remotely while the pet remains in its natural environment. While many AMs are commercially available and marketed to veterinarians,[9,10] none are fully validated, provide access to raw data, or have open-source algorithms; these are necessary for an outcome measure to be used in a regulatory study and sustain quality assurance.[11] In addition, AMs used in published veterinary studies[12–20] almost exclusively report an "activity count." Since there is no standard "activity count" in companion animals, nor an explanation of how it is calculated in quadrupeds, the clinical relevance of the activity count is challenging to interpret, particularly across different AMs. Furthermore, the direct translation of existing algorithms developed for people to quadrupeds seems speculative given obvious differences in morphometrics and activities performed (eg, people rarely jump from a height that equals their own or run at a full sprint).

Criterion validity is essential for the objective measure of physical activity. While there is extensive research addressing the criterion validity of accelerometers in people,[21–28] little work has been performed in dogs.[10] The critical steps of criterion validity are (1) concurrent validity to ensure the instrument measures what it is intended to measure compared to a gold standard and to establish interinstrument variability, and (2) predictive validity to document the extent to which the instrument functions relative to the purpose for which it is going to be used.[23,27]

The objectives of this research were to (1) document the accuracy and precision of IMU acceleration output relative to a known acceleration (gravity), (2) determine intra- and inter-IMU variability, and (3) demonstrate the relationship between IMU output (acceleration vector magnitude) and canine activity of varying intensity. We hypothesized that IMU output (acceleration vector magnitude) would (1) accurately and precisely measure a gold standard, (2) have low intra- and inter-IMU variability, and (3) be able to discern between activities of differing intensity in dogs.

Material and Methods

Animals

Twenty, client-owned dogs were enrolled in this prospective clinical study. The study protocol was reviewed and approved by the Institutional Animal Care and Use Committee (IACUC; No. 2204-39913A). Written, informed client consent was obtained before enrollment. Owners received a $25 VISA card as an incentive for participation. Inclusion criteria included the dogs had to be of adult age, have no reported health conditions, be normal on physical exam, and be trained to complete an agility course. Exclusion criteria included pregnancy, use of medications for neuromuscular or musculoskeletal disease, and an inability to successfully complete the agility course.

Before the activities were performed, dog breed, age, body weight (recorded using an electronic scale), body condition score (1 to 9), and length from the IMU to the ischiatic tuberosity (measurements were made by the same investigator using the same tape measure with the dog standing) were documented. The length of the IMU to ischiatic tuberosity was recorded to help normalize differences in subject center of mass.[29]

Inertial measurement units

Calibration of the inertial measurement units (Shimmer3 IMU; Shimmer Research) was performed according to the manufacturer's manual (*Shimmer 9DoF Calibration Application*; Shimmer Research) using the calibration stand. Before data collection, the IMU was programmed to a collection frequency of 51.2 Hz (default frequency that also would allow for capturing the majority of canine movements since sampling rates up to 20 Hz are reported to capture the majority of human movements) with a wide range accelerometry (± 8 *g*); no other filters or algorithms were applied.[30,31] Data collection was set to start and end when the IMU was undocked and then redocked, respectively. The IMU docking station was connected to a dedicated computer equipped with software (ConsensysPRO; Shimmer Research) designed for data download and storage.

To assess concurrent validity, acceleration output from 4 IMUs was compared relative to gravitational acceleration as a reference (x-axis = 0 m/s^2, y-axis = 0 m/s^2, and z-axis = 9.81 m/s^2) and compared to each other. After calibration, the IMUs were taped together in the same orientation, positioned at rest on a table with the z-axis directed toward the room floor and the x- and y-axis parallel to the room floor, after a period of 5 to 10 seconds the 4 IMUs were picked up and shaken for 5 to 10 seconds and then returned to the rest position on the table; this process was repeated 7 times. Before data evaluation, 200 data points of IMU output were deleted from the beginning and end of the experiment to ensure only data associated with the experiment was tested.

To assess predictive validity, an IMU device (51 mm X 34 mm X 14 mm) was secured into a neoprene battery holster (OP/TECH USA Battery Holster) and a nylon dog collar was fed through the sewn-in loop attachment and firmly secured in place. The IMU was placed away from the metal ring used for leash attachment on the collar to prevent interference. One of 2 IMU devices from the concurrent validity experiment was used throughout this predictive validity experiment; the IMU used was randomly selected (coin flip). Two IMUs were selected to decrease inter-IMU variability and ensure a backup IMU was available to complete data collection if needed. The collars were adjusted to ensure a snug fit so that the collar could not be pulled over the dog's head and that 2 fingers could fit between the neck and collar. The IMU was placed on the ventral neck as previously described.[6] Simultaneous video of all activities from IMU undocking to redocking was captured at 100 Hz using a camera phone (Apple iPhone 12 and iPhone 13; Apple Inc).

Data collection was performed over 3 separate days at a single indoor canine agility facility (Fusion Pet Retreat). An agility course was mapped out to ensure the same course and distances were prepared for each participant. The agility course consisted of 2 tunnels, an A-frame, and 4 jumps that were set to each participant's competition jump height. Before the collection of data, owners were instructed about the series of activities their dog would perform and they were allowed to familiarize their dog with the agility course.

The IMU device was undocked, placed on a table to rest for several seconds, shaken approximately 10 times, and placed in the neoprene case ventrally on the dog's neck, and then the activities were initiated. The initial resting and shaking of the IMU were to help ensure IMU and video output was synchronized by creating recognizable acceleration vector magnitude (VM; VM = sqrt[$x^2 + y^2 + z^2$]) output (VM is a flat line when resting on a table is and VM is a sinusoidal waveform when shaken). The dogs (with the owner's guidance) performed the following activities: rest (sitting or laying down) for 15 to 30 seconds, a walk on a leash led by the owner for 30 to 60 seconds, rest for 15 to 30 seconds, a trot on a leash led by the owner for 30 to 60 seconds, rest for 15 to 30 seconds, and repeated completion of the agility course for 60 seconds. Dogs repeated this activity series 3 times with a rest period of 15 to 30 minutes between each repeat. The same IMU was used for all of the dog's data collected for the 3 repeats. At the completion of a series of activities, the IMU was removed from the collar and redocked. IMU data (.csv file) and video output were downloaded and reviewed after each trial to ensure data were collected. Digital output (IMU and video) was manually synchronized by matching the initial IMU output (when the IMU was removed from the docking station) to the video of the IMU removed from the docking station and documenting this as 0 seconds. Synchronization was checked by confirming the IMU output when resting on a table, when shaken and when redocked.

Dog activities were categorized as rest, walk, run, or agility by a single investigator using direct observation from the video, and a time stamp from the video was recorded. For example, when a dog was seen to begin a period of rest, a time was recorded; when that period of rest ended, a time was recorded. Since the synchronization process could have been incorrect by fractions of a second, 1 second plus any fraction of a second were removed from the activity time stamp at the beginning and end of each activity. For example, if a dog began a period of rest at 45.67 seconds on the video, the time stamp recorded for statistical evaluation was 47.0 seconds. While this resulted in slightly less data for evaluation, it helped ensure the IMU output was correctly associated with the intended observed activity. Transitions between specific activities were not tested. The direct observation time stamps of the first investigator were confirmed by a second investigator.

Statistical analysis

Since we found no description of the variability of acceleration VM between different exercise intensities in a heterogeneous population of dogs, IACUC approval included an initial investigation of 20 dogs followed by statistical evaluation and, if needed, an additional 20 dogs could be studied. Summary morphometric statistics are presented as mean ± standard deviation (range).

Acceleration output (.csv file) was evaluated using RStudio (RStudio Inc; Version 2022.02.3 + 492). While raw acceleration data for the x-, y-, and z-axis are IMU output, VM was also IMU output and was evaluated because, when in use, IMU orientation is constantly changing. A 1-second epoch was created by using the percentiles computed for each second of data.[25,30,32–34] Values of interest included the median acceleration (g_m), and the acceleration difference between the 10th and 90th percentile (Δg_{80}). All VM values were converted to g-forces (1 g = 9.81 m/s^2) so that the expected value of g_m at rest was 1.0.

For concurrent validity, 5,955 consecutive data points that were simultaneously collected from each of 4 IMU devices were evaluated for intradevice and interdevice reliability. To estimate the accuracy and precision of IMU acceleration output relative to a known acceleration (gravity) and intradevice reliability of g_m and Δg_{80} when the device was at rest, the mean and standard deviation were calculated for each device for the rest portions in the first and second minute separately. We would expect g_m to be consistently near 1.0 and Δg_{80} to be small. To estimate interdevice reliability of Δg_{80} when the device was in motion (defined as mean $\Delta g_{80} > 0.3$), intraclass correlation between the devices was evaluated. To estimate the concordance between devices, we computed the relative differences between the value for each device and the mean across devices and reported the median absolute deviation and the 95th percentile of deviation.

For predictive validity, the recorded time stamp from each activity (rest, walk, trot, and agility) was compared to VM. To determine the interdog and intradog variability of Δg_{80} at each activity level, random effects models were fit with terms for dog, trial, and period within trial (for the rest data only). The percent variation (the increase or decrease over time as a percentage) over time for each term was reported. Finally, to determine if Δg_{80} was useful in distinguishing the activity levels of the dogs, optimal cutoffs across all dogs were determined using the average percent agreement across all 4 activity types.

Finally, to determine if there was an influence of morphometrics on IMU output,[29] individual optimal cutoffs were first computed for each dog separately using the average percent agreement across all 4 activity types for each individual dog. These cutoffs were then used as responses in linear regressions, 1 for each cutoff, using the distance from IMU to ischium as the predictor variable. These were then used to make equations for cutoffs based on this distance, and the average percent agreement again computed for each dog.

Results

When the 4 IMU devices that were taped together were at rest, mean g_m across all 4 devices and the 8 rest periods ranged from 0.989 to 1.03 g

(SD < 0.0005), and the mean Δg_{80} ranged from 0.0031 to 0.0047 g (SD < 0.0005; **Figure 1**). When the 4 IMUs were in motion (defined as mean Δg_{80} > 0.3), the intraclass correlation of Δg_{80} between devices was at 0.995. For concordance between devices, the median absolute deviation from the mean across the 4 devices was 1.5% and the 95th percentile was 6.2%.

Twenty healthy adult dogs were enrolled and completed the study **(Figures 2 and 3)**. The population included 8 spayed females, 2 intact females, 5 neutered males, and 5 intact male dogs. Border Collies (n = 5) were the most common breed followed by mixed breed dogs (3), Miniature Australian Shepherds (2), Australian Shepherds (2), and 1 of the following breeds: Bull Terrier, Labrador Retriever, Doberman Pinscher, Portuguese Water Dog, Dachshund, Flat Coated Retriever, English Setter, and Miniature American Shepherd. Mean subject age was

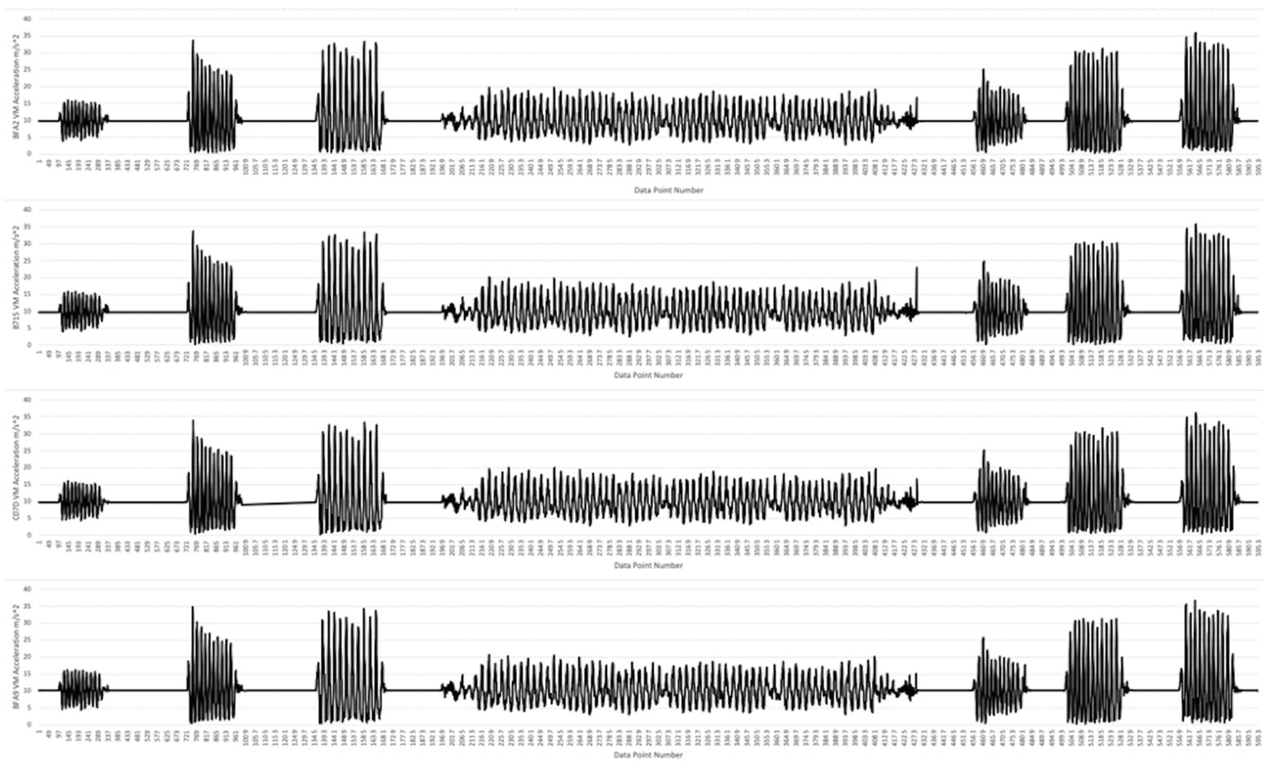

Figure 1—Acceleration vector magnitude (y-axis) simultaneously collected from 4 inertial measurement units (IMU). Seven cycles of rest and shaking were performed to document the accuracy and precision of IMU acceleration output when at rest (flat lines) relative to a known acceleration (gravity = 9.81 m/s^2) and to determine intra- and inter-IMU variability when at rest and in motion.

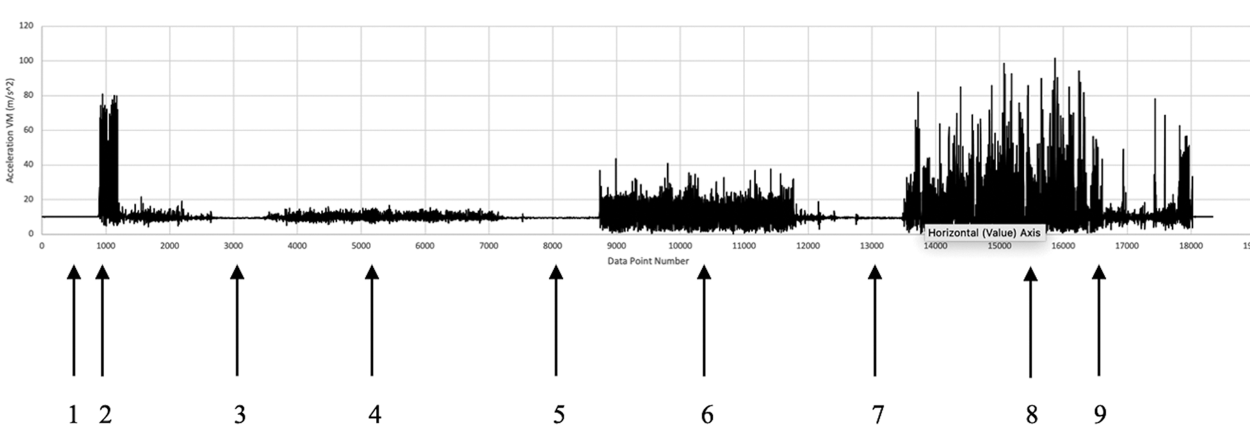

Figure 2—Overview of acceleration vector magnitude from a single session from undocking of inertial measurement unit (IMU) to redocking of IMU. During this session, 18,338 data points were generated. Numbered arrows identify different aspects of a session. 1 = IMU resting on table; 2 = shaking the IMU; 3 = dog resting period 1; 4 = dog walking; 5 = dog resting period 2; 6 = dog trotting; 7 = dog resting period 3; 8 = dog performing agility; and 9 = agility trial ended.

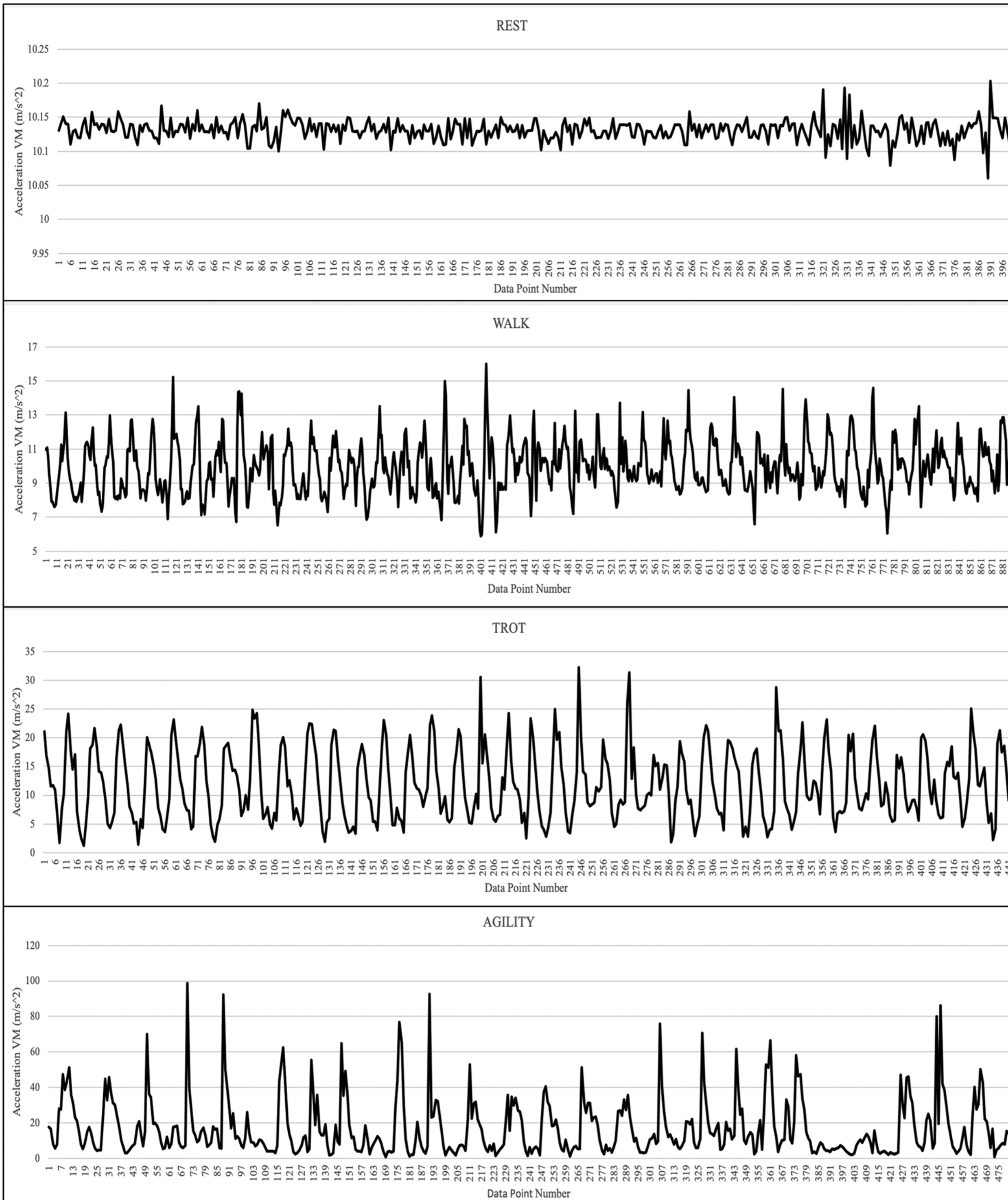

Figure 3—Example of selected data points from a session used to identify activities performed by a dog enrolled in the trial. Note that although there the waves formed for each activity appears similar, the magnitude of acceleration (y-axis) differs.

4.9 ± 1.7 years (range, 1.5 to 7.0 years). Mean subject body weight was 16.4 ± 8.0 kg (range, 4.9 to 30.7 kg). Mean subject BCS was 4.6 ± 0.5 (range, 4 to 5). Mean length from the IMU to the ischiatic tuberosity was 59.9 ± 11.4 cm (range, 41.0 to 79.0 cm).

Interdog variability of Δg_{80} at rest, walk, trot, and agility when output was not adjusted for subject morphometrics was 28%, 52%, 44%, and 18%, respectively **(Table 1)**. The optimal Δg_{80} cutoffs for all dogs in this population were rest at < 0.25 g, walk

Table 1—Percent variation within and between dogs for each activity.

Activity	Interdog variation	Intradog variation
Rest	28%	24%
Walk	52%	13%
Trot	44%	10%
Agility	18%	2%

at 0.25 to 1.15 g, trot at > 1.15 to 2.44 g, and agility at > 2.44 g. With the use of these VM Δg_{80} cutoffs across all dogs, the median proportion of activities correctly identified was 80.2% (range, 38.3% to 93.7%) **(Figure 4; Supplementary Figure S1)**. Using morphometrically adjusted cutoffs (linear regressions associated with distance from IMU to ischium), the median proportion of activities correctly identified slightly declined compared to the overall cutoffs, from 80.2% to 77.4%, although the mean proportion correct increased from 76.9% to 77.9%, and the minimum proportion correct increased from 38.3% to 57.0%.

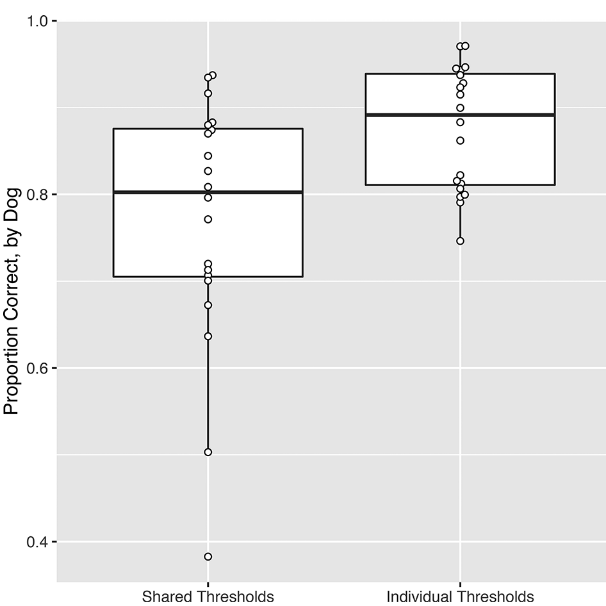

Figure 4—The median overall proportion identified correctly using the acceleration difference between the 10th and 90th percentile (Δg_{80}) cutoffs for all dogs (left) and individual dogs (right). For all dogs, 80.2% (range, 38.3% to 93.7%) were correctly identified without adjusting for participant morphometrics (data shown).

Intradog variability of Δg_{80} at rest, walk, trot, and agility was 24%, 13%, 10%, and 2%, respectively. The optimal Δg_{80} cutoffs for individual dogs in this population were rest at < 0.38 g, walk at 0.38 to 1.25 g, trot at 1.26 to 2.30 g, and agility > 2.30 g. This is the maximum improvement possible because this treats each dog individually and thus takes each dog's morphometrics into account. When individual cutoffs were created for each dog, the median overall proportion correct was 89.1% (range, 74.6% to 97.1%).

Discussion

In this study, we found that when the IMUs were at rest, VM was within 1.1% of a standard (gravity) with very small variation. Thus, we accepted our hypothesis that IMU output would accurately and precisely measure a gold standard. When the IMUs were in simultaneous motion, intraclass correlation and concordance between the 4 IMUs tested were excellent;[35,36] thus, we accepted our hypothesis that IMU output would have low inter-IMU variability. While alternative methods of testing acceleration are available (eg, having the IMU on a rotating fan of known radius and revolutions/minute or using a shaker device), we elected to perform a test that could be easily performed as a standard operating procedure before the use of any IMU or accelerometer in a clinical investigation. Many IMUs (including the one used in this study) provide real-time Bluetooth data reporting. Following calibration, investigators could check acceleration output relative to what is expected from gravity with the IMU at rest before placing the IMU on a clinical patient.

In this study of a heterogeneous population of dogs, we found that activities of different intensity could be correctly identified (Δg_{80} acceleration VM unadjusted or adjusted for subject morphometrics) approximately 80% of the time across all dogs and approximately 90% of the time for individual dogs. Thus, we accepted our hypothesis that IMU output would be able to discern between activities of differing intensity in dogs. It was expected that the proportion of activities correctly identified in individual dogs would be higher than across all dogs because subject morphometrics does not influence output from an individual dog. Subject morphometrics can influence acceleration output because the IMU is at a different distance from the subject's center of mass.[29] Although we found adjusting acceleration output relative to subject length and body weight[29] had little impact on the mean or median proportion of activities correctly identified, it improved the minimum proportion correct by nearly 20%. It seems prudent to utilize this adjustment when acceleration is studied in a heterogeneous population of dogs.

Moving forward, work could be performed to attempt replication of these results. Assuming similar results, then the "group cutoffs" determined could be used in clinical studies with this, or a similar, device. Another aspect that could be investigated is whether our determined cutoffs hold true for activity in the home environment, which is likely predominately off-leash. Since the walk and trot took place with the dog on a leash, by default the owner selected subject velocity for these activities and different owners likely selected different walking and trotting velocities. The influence of the owner on subject walk and trot velocity is likely an important contributor to the large difference in variation we found between interdog and intradog variation for these 2 activities. The influence of the owner may be less important in a clinical trial because (1) dogs are likely not on a leash most of the time when in their natural environment, and (2) dogs are likely not often on a leash when performing moderate to vigorous activities. This could be important because people that suffer from chronic pain reportedly spend less time performing moderate to vigorous activity.[37,38] In this study, interdog variation was comparatively low when dogs performed agility activities, again suggesting the influence of the owner on leash-direct activities is large.

We elected to use the devices described because they provided a fast sampling rate, sufficient data storage and battery life for the proposed work, access to all raw data, control of all algorithms, software that allowed for IMU calibration, easy data download and proved to be reliable when we performed concurrent validity testing. There are likely other accelerometers that would be reasonable alternatives. The sampling rate used, 51.2 Hz, was the default when the IMUs were calibrated. While we could have changed this, we selected a relatively fast sampling rate to ensure the capture of the majority of movements. Sampling rates up to 20 Hz, are reported to capture the majority of human movements.[30,31] We believe this is also true in dogs; exploration of accelerations induced by dogs jumping over an obstacle and landing in this study could have been consistently identified with a sampling rate of 20 Hz. While a faster sampling rate ensures all activity is captured, a fast sampling rate results in an enormous amount of data; approximately 12,000 data points for each trial in this study. For translation to a clinical situation, data collection at 20 Hz for 14 days would generate over 24 million data points. Thus, identifying an IMU that had adequate data storage and battery life was essential and the development of statistical methods to rapidly manage and analyze this volume of data was considered. Access to raw data and reporting algorithms was important because it allows for easier interpretation between studies and it would be necessary for quality assurance.[11]

The IMUs used in this study also collect motion data from a magnetometer and gyroscope. We focused on acceleration VM because it has a strong correlation to metabolic equivalents in people[27,30,39] and would be easy to reproduce for future research. The 1-second epoch (time interval of a data set)[25,30,32–34] was selected because it has been reported that short epochs are needed to classify physical activity when a short burst of vigorous activity could be expected[40] and if newer methods are being developed.[30] The mathematical description of output for the epoch can vary from a simple sum, mean, or median to something slightly more complicated like a percentile. We focused on the difference between the 10th and 90th percentile (Δg_{80}) of acceleration VM for each second of data across the duration of recording because this would report a range of acceleration generated by motion. In effect, less motion results in less acceleration and deceleration and a smaller delta between the 10th and 90th percentiles of output; larger motions result in larger accelerations and decelerations and a larger delta between the 10th and 90th percentiles of output.

This clinical investigation only studied normal dogs performing scheduled and, at times, owner-led activities. The clinical importance of measuring time spent at rest or performing light, moderate or vigorous activity in dogs remains unknown. It may be that dogs with chronic pain spend more time at rest or less time performing moderate to vigorous activity compared to a population of normal dogs, as suggested recently,[41] but this has not been investigated using validated methods. Similarly, one could investigate activity dogs with cardiovascular disease before or after an intervention or the IMU could be used to monitor subject activity after surgery to confirm activity recommendations.[42,43] Also, the population studied did not include extremes in subject age and morphometrics. This study did not include exclusion criteria beyond adult dogs and the population was heterogeneric but, there are several populations not represented including puppies, elderly dogs, obese dogs, toy, or giant breed dogs.

In conclusion, acceleration VM from the IMU studied provided valid data because it accurately and precisely measured a gold standard, had low intra- and inter-IMU variability, and was able to discern between activities of differing intensity in the majority of dogs in our study.

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Supplementary Materials

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