Evaluation of an accelerometer for at-home monitoring of spontaneous activity in dogs

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Objective—To determine the correlation between activity as measured by an accelerometer and videographic measurements of movement and mobility in healthy dogs.

Animals—4 healthy dogs.

Procedures—After determination that accelerometers had good agreement, 5 identical accelerometers were used simultaneously to test their output at 8 locations (rotated among collar, vest, and forelimb stocking locations) on each dog. Movement and mobility for each dog were recorded continuously with a computerized videography system for 7-hour sessions on 4 consecutive days. Accelerometer values were combined into 439 fifteen-minute intervals and compared with 3 videographic measurements of movement and mobility (distance traveled, time spent walking > 20 cm/s, and time spent changing position by > 12% of 2-dimensional surface area during 1.5 seconds).

Results—96% of values compared between the most discordant pair of accelerometers were within 2 SDs of the mean value from all 5 accelerometers. All mounting locations provided acceptable correlation with videographic measurements of movement and mobility, and the ventral portion of the collar was determined to be the most convenient location.

Conclusions and Clinical Relevance—Use of an accelerometer was adequate for at-home activity monitoring, an important end point in clinical trials of treatment for chronic disease, and provided information about daily activity that is unattainable by other methods. (Am J Vet Res 2007;68:468–475)

Assessment of quality of life has become an important component of clinical research in human and complements traditional clinical trial end points such as survival rate, mortality rate, and function testing.1 Conceptually, quality of life is a multidimensional construct that may include assessment of physical function, psychological well-being, and social function. Although measurement of physical function typically involves controlled tests in a laboratory or office setting, there is increasing interest in assessing the mobility and activities associated with everyday life. Similarly, veterinary researchers are beginning to supplement in-office assessments with evaluation of behavior at home to assess health and quality of life in companion animals.2,4

Mobility and spontaneous activity are compromised by chronic disease.1 These characteristics are being measured by researchers investigating quality of life and treatment effects in humans with chronic illness. The relevance of this approach is illustrated by the finding in humans with chronic heart failure that impaired mobility at home (as measured with a pedometer) is a strong predictor of early death. In that regard, this test outperforms the standard test of in-office treadmill exercise capacity.5 New insights into the value of treatment may also be gained by at-home measurements. For example, a study of the treatment effect of vasodilators in humans with heart failure and disease-limited activity revealed no improvement in daily activity at home even though in-office exercise capacity was improved.5 This finding suggests that although forced-exercise capacity improved with treatment, treatment failed to improve this aspect of the patient’s quality of life in a meaningful way.

Impaired mobility commonly complicates chronic pain syndromes, and its improvement is a primary therapeutic goal. In fact, mobility and activity are now considered to be important outcome measures and provide information that cannot be obtained from patient self-reports.7 Researchers have long realized that assessment of physical function at home is essential for clinical trials8 of treatment for chronic pain, even though the value of such assessments is limited when assessment depends exclusively on patient self-reports.7 Therefore, there is increased emphasis on obtaining objective measurements of activity at home to supplement other measurements.

Mobility is also considered to be an important indicator of well-being in dogs, and mobility-related charac-

ABBREVIATIONS

<table>
<thead>
<tr>
<th>DSS</th>
<th>Down sampling step</th>
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<td>MDM</td>
<td>Minimum distance moved</td>
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teristics are part of quality-of-life assessment in this species.** Historically, outcome assessments for veterinary clinical trials of treatments for heart disease have used measurements of survival, echocardiographic indices, arrhythmia, renal function, or hemodynamic measurements.** There have been few attempts to quantify the impact of treatment on owner assessment of quality of life or on objective measurement of activity in the home environment. One example of assessing the quality of life of dogs with congestive heart failure is the functional evaluation of cardiac health questionnaire, which is an owner questionnaire.** Of 17 weighted questions regarding various aspects of cardiac health, 5 are directly related to impaired activity and 2 are related to inability to lie quietly.

A relatively new method of assessing behavior at home uses an accelerometer to estimate activity. Most studies performed to validate these devices have compared them with measures of energy expenditure such as calorimetry** or oximetry.** A few studies have evaluated accelerometers with subjective visual assessment of behavior in humans** and dogs.** No studies have been conducted that correlate accelerometer data with objectively measured motion or distance moved.

The purpose of the study reported here was to determine the correlation between activity as measured by an accelerometer and videographic measures of movement and mobility in healthy dogs. Our hypothesis was that the coefficient of correlation between activity counts generated by the accelerometer and videographic measures of movement and mobility in freely moving dogs would exceed the correlation previously reported between a similar measure of activity (pedometer) and owner-reported activity of dogs (r = 0.305).** In addition, we sought to determine the location and method of attachment of the accelerometer that corresponded best with videographic measures of movement and mobility in dogs.

### Materials and Methods

All experiments were approved by the Animal Care and Use Committee at North Carolina State University and were performed in accordance with the National Institutes of Health policies on the use of laboratory animals and clinical subjects.

**Accelerometer**—To identify the optimal location to attach the device, 5 accelerometers** were attached to each dog in different locations by means of collar, vest, or forelimb stockings. The accelerometer is small (28 × 27 × 10 mm) and attaches directly to a thin collar in small dogs or cats or may be secured with twist-ties or sewn to larger collars, instrumentation vests, or stocking material (Figure 1). The accelerometer includes an omnidirectional accelerometer that uses a cantilevered rectangular piezoelectric bimorph plate and seismic mass. It is sensitive to movement in all directions but most sensitive in the direction parallel with the longest dimension of the accelerometer case. The piezoelectric sensor generates a voltage when the device is subjected to a change in velocity per unit time (acceleration). The voltage generated by the sensor is amplified and filtered by use of analogue circuitry. This filtered and amplified voltage is then passed into an analogue-to-digital converter within a microprocessor to create a digital value. This analogue-to-digital conversion and the following operations are repeated at 32 Hz. The digital value is used to adjust a running baseline value (mean of 32 consecutive readings obtained during a period of 1 second) that permits filtering out constant accelerations such as those caused by gravity. The current digital value is compared with the baseline value. The difference from baseline is added to a 1-second accumulated activity value. After 1 second, the value is divided by 4, then added to an accumulated activity value to create a raw activity value for the measurement period (epoch) and the 1-second accumulated value is reset to 0. The epoch is determined by the investigator and can be set at 15-second increments up to a maximum of 1 minute. The raw activity value is compressed into an 8-bit unsigned integer and converted into a 15-bit unsigned integer by the computer software and reported as an activity count after a calibration constant (built into the individual accelerometer) is applied. For purposes of the present study, the accelerometer data epoch was set at 1 minute because this will allow researchers in future studies to collect clinical trial data for the longest period of time (by use of 1-minute epochs, each unit can record and store data for 45 consecutive days).

**Video analysis**—A room was subdivided into an area for equipment and a separate observation area (called the arena) for recording movement and mobility of individual dogs. An overhead black-and-white composite video camera was mounted in the ceiling perpendicular to the floor above the center of the arena. Output from the camera was routed to a digital video recorder and a computer running a movement tracking system. In the computer, the composite video image was digitized with a PCI image capture card, and the data were routed to a proprietary software system.

The longest dimensions of the arena were 215 × 280 cm (Figure 2). The system was calibrated to convert pixels to distance in centimeters by placing 21.6 × 27.9-cm sheets of paper uniformly throughout the arena. The dimensions of each sheet were entered into the software by use of its calibration function until an SD from the mean calibration measurement in both the x
and y coordinates stabilized at 6%, a value that required 69 measurements. This deviation from the mean exists because of the variable distances from each calibration surface to the camera; for example, the periphery of the arena is farther away than the floor surface directly underneath the camera.

The system was calibrated to recognize a dog on the basis of the gray-scale density of the video image of its black saddle and black vest top, compared with that of the surroundings. The software acquisition characteristics and thresholds for inclusion and exclusion of image density were set to reliably capture the dog’s image in all portions of the arena with minimal noise from background objects. Four dogs were individually recorded for seven 1-hour-long sessions each; these 7 hour-long sessions were repeated daily for 4 days to generate 112 recording tracks in total. The completed motion tracks from each session were inspected graphically to ensure that there were no tracking errors by the system (Figure 3).

**Experimental protocol**—To characterize interunit variation, all 5 accelerometers were simultaneously mounted on the collar of a dog that belonged to a study technician. To expose the 5 accelerometers to similar forces, they were oriented in the same direction and 2 pairs (consisting of 1 unit stacked atop another) were attached to the collar on either side of the fifth accelerometer. Activity was measured by all 5 accelerometers at 1-minute epochs for 2,085 minutes. Halfway through this data collection period, the position of each accelerometer was changed and the data obtained during the 13 minutes it took to accomplish the position change was discarded, leaving 2,072 minutes for analysis.

In the movement validation phase of this experiment, 4 random-source mix-breed dogs (weight, 18 to 28 kg) were each studied for 4 days. The dogs were determined to be healthy and normally active by use of physical examination and observation by 2 authors (BDH and AET). To optimize detection of valid movement and determine the best location for placement, the 5 accelerometers were attached to different locations on the dogs by sewing them to a vest, a collar, and forelimb sleeves. Because only 5 accelerometers were available, not all locations were evaluated at the same time. Three locations (bottom of a collar, a pocket in a vest over the lateral portion of the thorax, and the bottom of the caudal edge of the vest over the abdomen) were used for the entire experiment because they were convenient; other locations were evaluated for shorter periods. Across the 16 observation days (4 dogs × 4 days each), the 8 locations evaluated included the top (12 days) and bottom (16 days) of a collar, the axilla (4 days), the lateral portion of the humerus (4 days), the antebrachium (4 days), the lateral portion of the thorax (16 days), under the sternum (8 days), and under the abdomen (16 days; Figure 4).

The time stamp on each accelerometer and the digital video recorder were electronically synchronized with the clock in the computer that ran the videography system. The accelerometers were programmed to begin recording 20 to 60 minutes prior to the onset of each trial to allow time for proper fitting and to set up the movement-tracking system. The characteristics of the tracking system were optimized for each dog during a trial period of 5 to 15 minutes, and the system was set to begin recording at the nearest quarter hour. Each day consisted of 7 hours of recording, beginning between 8 and 9 AM. The dogs were allowed to roam freely within

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**Figure 2**—Photograph of a pen used for monitoring spontaneous movement and mobility in dogs via videography. Notice the operator-defined arena border (white lines) superimposed on the image.

**Figure 3**—Graphic representation of a dog’s movement in a pen during a 1-hour period (4 consecutive 15-minute intervals). The dog moved 503.5 m overall.

**Figure 4**—Photograph of a dog used to study spontaneous activity. Various locations for an accelerometer are indicated (arrows; a = top of collar; b = bottom of collar; c = lateral portion of the thorax in vest pocket; d = axilla, sewn to vest; e = lateral portion of the humerus, sewn to elastic fabric legging; f = antebrachium, sewn to elastic fabric legging; g = under sternum, sewn to vest; and h = under abdomen, sewn to vest).
the arena, and a technician played with them and offered them pieces of kibble by hand for 15 minutes at least once each day. Each dog had a water bowl and a fenestrated hard rubber ball filled with kibble that could be accessed by rolling the ball. The collar, vest, and leg-gings worn by the dogs were well tolerated and did not appear to restrict their movement in any way.

The videography recordings were collected as 7 consecutive 1-hour sessions to allow a portion of the day to be discarded, in the event of tracking errors, without loss of the entire day’s data. At the completion of each day, all accelerometer data were downloaded to the computer and the recorded epochs were trimmed to contain only the time periods recorded by the videography system.

Videography data—After the 2-dimensional surface area of a subject’s image was captured with the videography system, the software plotted the geometric center of the image as an x-y coordinate in a grid that contained the entire arena. For this study, the x-y coordinates were obtained at a sampling frequency of 6 times/s. This frequency was determined in preliminary trials performed prior to the study reported here. The preliminary trials were conducted on 5 dogs (including 3 of the 4 dogs in this study) of different sizes to calibrate the videographic system and determine the proper lighting and fabric colors necessary for accurate tracking. A range of sampling frequencies from 2 to 30 times/s were used to generate tracks that were visually compared with subject movements in real time during recording. The frequency of 6 samples/s was found to be sufficiently high to accurately capture rapid motion of dogs playing vigorously with a person in the arena.

To reduce potential artifacts in movement and distance (eg, measurements generated by breathing and image wobble during walking), the system can smooth the data by sampling only a portion of the data points (the DSS). In addition, an MDM value between 2 time points can be designated by the operator for the system to record the animal as moving or to measure distance moved. The optimal DSS filter settings were determined by repeatedly calculating the total distance moved from all tracks by use of progressively more restrictive filtering. Typically, when the sampling frequency is relatively high (3 to 30 samples/s) there are large reductions in total distance measures as the filter increases from 1 (every datum point included) to a DSS of between 2 and 3 (every other to every third datum point included). At the filter setting at which stepwise reductions in distance tend to diminish with increasing DSS, further reductions in distance detected with each increase in DSS value are caused by excessive attenuation of valid data. In preliminary trials with these data, stepwise increments in the filter were examined to a DSS of between 2 and 3 (every other to every third datum point sampled) was chosen as optimal for all comparisons.

Important sources of travel artifact for dogs include movement of the thorax and abdomen during respiration and the effect of moving only the head and neck while standing in 1 spot. The effect of these partial-body movements on whole-body movement measurements can be limited by requiring that the geometric center of the image travel some minimum distance since the last sample before that coordinate is included in data analysis. To limit this artifact, MDM filters of 0, 1, 2, 3, 4, 5, 10, 15, and 20 cm were examined to determine the effects on total distance traveled when a DSS of 3 was used. An MDM filter of 5 cm was chosen as the distance-traveled filter because it did not attenuate the data excessively and, on visual inspection of the images during recording, was more than large enough to filter out all respiratory artifact.

With a record of the subject’s dog’s coordinates in the calibrated arena updated every 0.167 second for the duration of the recording sessions (prior to filtering), the software provided data regarding location, distance traveled, velocity, movement, and mobility. Within the videography system, distance, movement, and velocity characteristics were generated when the position of the geometric center moved beyond operator-determined thresholds of distance per unit time, whereas the mobility characteristic was generated when the aggregate location of all the pixels making up the animal’s image shifted by greater than another operator-determined threshold percentage. Thus, movement was recorded when the position of the geometric center of gravity changed position above its threshold, and mobility occurred when the image shifted above that threshold, even if the position of the geometric center did not change. Visual inspection of random segments of video footage prior to analysis revealed that dogs moving at a slow walking pace moved at least 25 cm/s. To capture the relationship between walking (vs other movement that did not comprise purposeful travel) and accelerometer output, a value of 20 cm/s was selected as the threshold for the videographic characteristic of moving, and a value 25% of this (identical to the MDM filter) was selected as the value for the characteristic of not moving.

In a process similar to choosing the optimal DSS and MDM, the percentage change threshold for classifying an animal as mobile was evaluated at each step as this threshold was increased in 1% stepwise incre-

![Figure 5—Bland-Altman plot of agreement between results obtained from the 2 most disparate of 5 accelerometers. The x-axis represents mean activity counts (per minute) of all 5 accelerometers; y-axis represents the difference between activity count values obtained from the 2 accelerometers for each of 2,072 one-minute epochs. Horizontal lines represent the mean difference across all time points and ± 2 SDs. Values > 2,000 counts/min represent vigorous activity; note that differences between the 2 units are larger when counts exceed that value. Notice that there are several groupings of activity counts that suggest the presence of linear relationships between accelerometers with certain types of activity or behaviors.](image-url)
ments from 0% to 15%. For this analysis, a DSS of 3 and an MDM of 0 were used and the data were further smoothed by use of a running mean value of 3 samples to calculate the mean pixel locations used for comparison with the next image. When combined with the sampling frequency of 6 times/s and DSS of 3, this allowed the software to compare the current image size and location with a mean value created by combining every third image over the preceding 1.5 seconds. A mobility threshold of 12% appeared to be the optimal value that reduced the effect of system noise yet still detected movement. This was determined by visual confirmation that the dogs did not move or moved very little during randomly selected 15-minute periods with mobility of 0 and that the mobility measure increased during segments when the subject dogs did appear to move. Thus, if < 12% of the pixels forming the image moved relative to a virtual mean location during the most recent 1.5 seconds, the dog was classified as immobile, and if ≥ 12% changed, the dog was classified as mobile during that time. With this measurement, a dog may have been classified as mobile even when its geometric center did not travel. For example, the surface area image of a dog sitting in 1 location and grooming itself could shift > 12% each 1.5 seconds without achieving threshold movement of its geometric center. In contrast, to be classified as moving, the geometric center had to shift by at least 20 cm/s.

**Statistical analysis**—By use of the data collected from the trial of accelerometers connected on the same collar, a paired output comparison was performed according to the method of Bland and Altman with a comparison made for every possible combination. The raw output from the units (1-minute epochs) was used for this comparison. To increase the resolution of comparison for the recorded portion of the study, the hourly videographic data were analyzed in 15-minute intervals and compared with accelerometer measurements obtained by adding fifteen 1-minute epochs from the same interval. An interval of 15 minutes was chosen as a useful interval to permit narrowing of the search window if it was needed to scrutinize video images to explain any discrepancies among the measures, yet long enough to minimize any consequence of small synchronization errors or brief intense stimulation of the accelerometers. Data collection ended at the completion of the fourth 7-hour day because the correlation coefficients did not change by > 0.07 for any location between days 3 and 4. Reduction of four 7-hour sessions from 4 dogs into 15-minute intervals created 448 samples. Nine of these were discarded because of tracking error (2 hours = 8 intervals) or premature removal of the dog during the last recording of the day (1 interval), leaving 439 intervals for comparison with the accelerometer measurement from each location. The data were not normally distributed because of skewing by a large number of values near 0 and a few values that were

![Figure 6](image-url)

Figure 6—Plots of correlation between 3 (A–C) accelerometer output values (counts/min) and distance traveled, time spent moving > 20 cm/s, and time spent at > 12% mobility for 4 dogs with an accelerometer located on the collar.
high. Spearman correlation coefficients between each accelerometer output and distance traveled, time spent moving, and time spent mobile by use of a mobility threshold of 12% were calculated. For all comparisons, $P < 0.05$ was considered significant.

**Results**

**Comparison of individual accelerometers**—Agreement within every possible paired comparison of the 5 accelerometer devices at low output values was within $\pm 2$ SDs, and most splay beyond this limit occurred during epochs with large accelerometer output (Figure 5). The percentage of comparisons that was outside of $\pm 2$ SDs from the mean difference ranged from 2% to 4%, which was considered acceptable.

**Validation against videography**—The dogs had a wide range of values for movement and mobility. Median total distance that each dog traveled in 1 interval was 30.1 m (range, 0 to 261 m; interquartile range, 10 to 68 m). The correlation coefficients among the various combinations of distance traveled, time spent moving, and the accelerometer output from the 8 locations were similar and ranged from 0.71 to 0.93. The mobility measure correlation was poor for some locations (as low as 0.19 for the humerus). Although the correlation coefficients for distance traveled and time spent moving were sufficiently similar to predict no substantial impact on clinical use, the ventral portion of the collar may be the best single location for clinical studies because of the convenience of that site. The correlation coefficient between the collar accelerometer and distance traveled and time spent moving $> 20$ cm/s was 0.89 ($P < 0.001$) and for mobility was 0.88 ($P < 0.001$; Figure 6).

The data were arranged graphically against time to determine reasons for disparity between the accelerometer output and videography-derived measurements at discrete time points, and the time scale was calibrated to create the closest approximation between the videography and accelerometer results for dogs B and D to help illustrate the difference between those 2 dogs and dogs A and C (Figure 7). When the dogs rested quietly, all measurements were near 0. With movement, all measurements increased, although the proportional

![Figure 7](image-url)
increase for each varied by dog. For example, the proportional change in accelerometer and videography measurements on day 3 for dogs B and D were similar from hour to hour, whereas they were different for the other 2 dogs. The data from dog A revealed splay between individual videography measurements and the accelerometer output as activity increased, and the data from dog C revealed systematically increased accelerometer output at all times, but particularly when more active. Similar effects were found in the data from the other days. The software related to the accelerometer was capable of graphing the raw activity value output into a time scale as determined by the user-defined epoch interval (Figure 8).

Discussion

To the authors’ knowledge, the study reported here is the first to compare accelerometer measurements against objective measurements of movement and mobility in dogs. Computer-assisted videography is widely used to characterize movement in many species and has been validated against a number of other measures of movement and activity.14 In the present study, an accelerometer mounted on any of 8 locations provided a good approximation of movement, with Spearman correlations ranging from 0.71 to 0.93 for all comparisons with distance and time spent moving. Because the ventral portion of the collar is likely to be the most convenient and well-tolerated location for most owners and dogs, it seems an appropriate location for further study.

Each of the 3 videography measurements used in this study assess activity in related yet different ways. Distance traveled is perhaps the most straightforward measurement for comparison, but requires that the animal’s position changes over time and does not account for activity when not changing location. Examples of behaviors that involve motion but do not require traveling include eating, scratching at the collar, and shaking to dispel water from the coat. These behaviors may strongly stimulate a collar-mounted accelerometer but do not involve travel. However, these and similar behaviors are characteristic of robust health and may be relevant to studies of animals with poorly controlled pain, orthopedic or neurologic injuries, or heart failure.

Movement, as defined by the criteria set in this study, was an approximation of the time dogs spent in motion at a velocity judged to represent purposeful walking. That velocity was determined by use of a subjective process based on screening video recordings for times when the dogs walked slowly towards an apparent goal. The cutoff thresholds used for movement (20 cm/s for moving, 5 cm/s for not moving) seemed appropriate as judged via visual inspection and corresponded with the other videography-derived variables.

Time spent mobile is affected by position change and is therefore related to distance traveled and movement. However, because it is also affected by motion not associated with traveling, the measurement of mobility can include other aspects of activity that might be registered with an accelerometer. Indeed, inspection of the interval data revealed several hours with relatively high mobility and low movement. The relatively poor correlation between mobility and the accelerometer output when located on the humerus may have been caused by excessive stimulation by limb movement that did not register as mobility at the settings used in this study.

Despite the qualitative differences of the 3 videographic variables used in this study, the strength of the correlation between the accelerometer output and each measurement was similar, which suggested that there was a robust relationship between the accelerometer measurements and different types of movement. In particular, the relationship between the accelerometer and videography measurements was strong during periods of inactivity, which was in accordance with the purpose of the device. The splay among individual videography measurements or between videography measurements and accelerometer output as activity increased for some dogs at some time points may be explained by the particular behaviors the dog engaged in at that time. For example, vigorous tail wagging that includes whole-body movement may exaggerate the mobility measure relative to both the accelerometer output and distance traveled measurements. The accelerometer was not stimulated proportionally because the primary axis of movement at those times was side to side, perpendicular to the long-axis orientation of the collar unit. The distance traveled was also proportionally less because during wagging, the dog’s torso bent to the left and right around its geometric center, which did not reach the MDM threshold set for moving and distance traveled unless the dog walked simultaneously. The data from dog C revealed a systematic increase in accelerometer output, compared with the videography-derived measurements. When not walking during hours 1 to 6, this dog spent most of the time lying in 1 location while
vigorously sniffing the ground or chewing on a blanket. Both of these behaviors involved rapid, repetitive up-and-down movement of the head and neck that stimulated the accelerometer but did not cause movement or mobility measurements to exceed the threshold for detection. Thus, the accelerometer output was proportionally higher every hour for that dog and decreased as the dog began to sleep more during hours 6 and 7.

Because clinical trials of treatment effect by use of the accelerometer to monitor activity would ideally include before-and-after measurements in a crossover study design, these individual idiosyncrasies should have minimal impact on measurement unless the subject dog adopted fundamentally different behavior patterns along with any change in overall activity and movement. However, such changes might represent an important outcome, depending on the study design and goals of the intervention.

At least 2 lines of investigation are appropriate to study the relevance of accelerometer measurements to canine heart failure, chronic pain, or other activity-limiting disorders. One is to compare diseased dogs with age-, size-, and environment-matched clinically normal control dogs to determine whether these disorders actually affect activity or its temporal distribution. The other is to obtain baseline data on dogs with one of these disorders, institute treatment, and repeat the measurement. The accelerometer used in this study can continuously record data for up to 42 days, allowing ample time to obtain data after treatment. Another advantage of the accelerometer is its ability to characterize the temporal distribution of activity. For example, dogs with heart failure or chronic pain may have difficulty sleeping comfortably for long periods at night, a feature that can be detected by an increase in activity at inappropriate times.

The accelerometer provides a unique method to quantify activity at home for comparison against owner assessments and in-office tests. Although it must undergo further testing in the home environment, it may prove to be a valuable method to assess veterinarians’ ability to achieve a primary therapeutic goal, improved quality of life, when treating dogs with chronic illness.

References