Kinematic Modeling of Canine Limb Motion during Toy Retrieval Activities

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ABSTRACT

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Toy retrieval is a common exercise used by pet owners in today's society for domestic dogs (*Canis lupus familiaris)* but the impact of the exercise on the dog's joint health is not well characterized. The acceleration of dogs and the mechanics of jumping agility hurdles are well-studied, however there is less knowledge about how dogs decelerate and how this impacts the strategies they employ to chase the toy. If a difference in the acceleration and deceleration motion between compromised joints and sound joints is found and quantified for retrieval, the veterinary field can improve early diagnostics and treatment of joint conditions. The aim of this study is to quantify the natural joint motion and variables affecting toy retrieval in dogs and to create predictive statistical models. This study recruited eighteen dogs with a variety of ages, breeds, and medical backgrounds to run retrieval trials. Video recordings of the subjects retrieving thrown toys from their owners were recorded and the subjects' backgrounds were collected on a written survey. Kinematic analysis was performed on the videos to measure average horizontal velocity and maximum range of motion (ROM) detected in the knee and elbow joint angles. The analysis yielded two major results and categorized different strategies of acceleration and deceleration. The data showed that joint condition of the dog has a significant impact on the observed ROM of the knee joint during deceleration and the breed of the animal

was shown to impact the observed acceleration elbow ROM. The dogs either accelerated on command, whipped around to chase, and/or faced away from the owner to chase. The four types of deceleration employed were pouncing on the toy, skimming over it, catching it in mid-air, and/or running by and looping back to pick it up. From these data, statistical models were developed to predict the average ROM expected for a given combination of joint conditions, strategies, breed groups, and age.

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INTRODUCTION

There are millions of dogs that find joy in retrieving their toys thrown by their beloved masters. However, many of these dogs also endure joint issues later on in life. There has been a lot research done on the stresses dog's joints experience in agility competitions and daily activities; however, one exercise neglected in research is toy retrieval and its effects on joints [1,2,3,4,5,6,7,8,9,10]. As this activity is widespread there is a need for this information. Joint damage and parameters of the dog type may show correlations to certain motions in retrieval. In addition, most current literature is very specific to certain breeds of dogs but lacks comprehensive results across multiple types [11,12,13,14].

It is clear from the sports medicine world, injuries sustained during sports can negatively affect the athletes' health later in life. Even, if the athlete does not suffer major injuries during their career, minor traumas sustained during the sport can impact their health as they age. However, in the animal world, it is uncertain if this is true. Articles recently published claim that joint health is not negatively affected by lifelong exercise but the disuse of joints could led to complications [15,16,9,17,18]. Research done by Ragetly and colleagues determined that there was a visible difference in limb motion on a treadmill between clinically normal dogs and dogs predisposed to cranial cruciate ligament disease [19]. However, is it also possible that a dog's preferred sport could negatively impact it later in its life? The dogs in the Newton study were exercised by on a treadmill with various weight they must support, however this is a very different kind of exercise than retrieval [9]. The acceleration of dogs on a runway is well studied, but the deceleration of running dogs has not been characterized [3,10]. Retrieval requires the dog to not only accelerate, but to make sharp turns, adjust speeds, coordinate their catch, and decelerate. Among these actions, both acceleration and deceleration are reasonably uniform across dogs making it target for comparison among dogs and they are good indicators for muscle performance. But there are more systems that are affected by acceleration and deceleration. The repeated minor impacts of running are amplified with the greater forces generated with these actions. This is why acceleration and deceleration need to be quantified as they may be potential contributors to joints complications.

Besides joint condition these is also a potential for the dog's genetics and body type to have an effect on the measurable parameters of acceleration and deceleration separate from joint condition. As an example, a dachshund may not be able to achieve the same knee flexion as a greyhound because of the different proportions of their respective limbs. However, these effect of breed and joint health may not be separate either, because there is research to suggest that breed and genetic background do have a role in the dog's long-term skeletal health [20,12,13,21]. The Orthopedic Foundation for Animals reports a growing prevalence of joint issues in breeds pre-disposed to elbow and hip dysplasia, which frequently lead to arthritis [22]. They also report these diseases development in previously unaffected breeds [22]. Therefore a study on the acceleration and deceleration in retrieval cannot ignore breed in its analysis.

Beyond just age, breed, condition, the strategy employed by the dog may affect the acceleration and deceleration measurements. There are a variety of ways a dog can retrieve, ranging from catching the toy in mid-air to circling around to pick the toy up while headed back to the owner. Depending on how the dog decides to retrieve the toy, the acceleration and deceleration motion might vary drastically. As this is not well researched, especially for deceleration, a study needs to start categorizing the variety of strategies use by the dogs, as their decision may indicate their physical comfort level.

This research investigates the action of accelerating and decelerating during retrieval. Using a wide variety of dog types and joint heath, it determined a variety of correlations between these variables. The main question this study sought to answer was: what are the key parameters captured during retrieval exercises which can differentiate dogs with compromised and sound joints? As an observational study, it laid the ground work for future controlled experiments and predictions about a dog's future or current joint health. It is the first step in determining possible stresses that toy retrieval has on dog limbs, and whether those stresses can predispose a dog to joint issues.

The study aimed to quantify dog limb motion during the two phases of the retrieval process: acceleration and deceleration, and correlate those motions to distinct features of sound and compromised limbs. Further it created a Linear Mixed Effects model able to make predictions about the motion when given a set of background parameters, age, joint health, breed, and strategies used to retrieve the toy. It also created a preliminary database of observed kinematics during the dog's retrieval. This can help predict whether retrieval activities repeated over time can predispose the animal to joint issues.

Definitions

Compromised joints refer to limb joints that do not function normally, cause pain, and/or abnormal movement. Common examples of joint disorders are arthritis, dysplasia, and cruciate ligament deficiency.

Retrieval behavior is when the dog starting from within ten feet of the owner chases the thrown toy, catches it, and attempts to bring the toy back to the owner.

Standing still for the negative control involves the dog standing squarely on four feet with no shifting of feet and minimal sideways head movement. The dog must stand free from owner and tight leash restraint.

Kinematics refer to the motion of the dog's limbs and the study of that motion.

Viable Trial is when the dog successfully runs in between the cone runway lines perpendicular to the cameras and the two nearest limbs are visible to the cameras at all times. Also the dogs does not have excess extra movement to either side and brakes to catch the toy roughly in line before the end of the runway.

MATERIALS AND METHODS

The subjects were recruited from the local pet population, through flyers, social media exposure, and correspondence. Consent from the subject owners was obtained before any data collection. A total of 22 dogs were recorded ranging from beagle to mastiff mix, but only 18 of the subjects met the age requirement and completed viable trials. Only they were analyzed. These subjects were individually taken to one of three locations: a local dog park, an open soccer field at a local organization, or an owner's backyard, based on the dog's individual comfort level with new environments.

Trial Set Up

The experimental set up involved placing two rows of four to six low sports cones, ten feet apart from each other, in a runway fashion, to mark the area of recording. After ten or more minutes of adjustment time and practice toy tosses in the runway, three trials were collected on the dog's acceleration and deceleration in response to the thrown toy. Two Sony HD x60 video cameras recorded the acceleration phase and the deceleration phase of the dog on a randomly chosen side. The cameras were set up 25 feet away from the nearside of the runway and had an approximately 30 foot view of the runway. The set up for this experiment is portrayed in figure 1.

Data Collection

After three viable trials were collected, two other videos were recorded to act as negative controls for running motion. A video of the dog walking beside the owner for ten feet and a video of the dog standing still beside the owner was captured. After collection of viable trials, the limb and body measurements were taken of the dog by the researcher and recorded for kinematic analysis. The owners were asked onsite to fill in a brief survey of the dog's medical and exercise history specifically related to age and joint condition. The researcher also did a brief examination of elbow and knee joint mobility and collected limb size measurements, which are tallied in the appendix, table 2. The researcher's examined the range of motion (ROM) of all 4 limbs, and watched for whether the dog flinched or went stiff as a sign of pain when a limb was flexed. That with the owner-provided medical and exercise history was judged to assign each subject a category on joint health before data processing.

Data Processing

Following data collection, the videos were trimmed to the appropriate length, horizontally flipped if necessary so that all the dogs were running from left to right for computer analysis, and converted to mp4 files for import into the software MaxTraq © by Innovision system Inc. Six points were tracked on each dog: shoulder, elbow, wrist, hip (base of tail), knee, and heel, as shown from the subjects in figure 2.

Three strides were tracked starting from when one front paw was firmly planted on the ground and the hips were off the ground and mostly perpendicular to the camera and ground, as shown in figure 2 (B). Elbow and knee flexion angles were determined by the angle tool on MaxTraq © software. It measured the exterior angle of the knee and elbow. When tracked position was hard to determine due to video quality, the angles pattern mapped automatically on MaxTraq © Angle vs. Time graph provided ample information needed to estimate the location of the nonvisible point on the frame. A scale of 120 inches was set on the video frame using the scale tool in MaxTraq © by marking two cones locations in the runway. The difference from peak to trough of the Angle vs. Time plot on MaxTraq © corresponded to the elbow's (or knee's) furthest extension and retraction during the stride and counted as one range of motion (ROM) measurement. This was repeated for each viable trial in acceleration, deceleration, standing, and walking. In total, three acceleration datasets, three deceleration datasets, a standing video dataset, and a walking video dataset were collected from the five videos of a given subject. Following point and angle collection, the three maximum stride ROM measurements were taken for the statistical analysis.

In addition, due to the wide variety of breeds in the subjects, the breeds were grouped based on relative numbers of similar breeds and similar body type. The only exception to this was the Other group, which included subjects that could not be grouped in with other types. The groups were sorted into: Retriever, Shepherd mix, Lab mix, and Other. The golden retrievers, pure Labradors, and Goldendoodles were grouped together in the Retriever group. The Shepherd group included a German Shepherd, and a mix with only a confirmed shepherd background. The Lab mix group included dogs of mixed background but with some confirmation of Labrador in their background. As their body types ranged sustainably from pure Labradors in the Retriever group, they were made into a separate group. The Other group included all the subjects that didn't belong to the other groups: Siberian Husky, Beagle, Springer spaniel mix, and Draathar. Table 1 shows the number of subjects per group.

The categories were sound, susceptible, and compromised. Sound dogs had no issues historically and had easy full ROM in elbow and knee. Dogs who were susceptible had near full ROM and no pain flexing or extending the limb, but had been previously injured and/or had early symptoms of dysplasia or arthritis. Compromised dogs were clinically diagnosed by a veterinarian and had limited ROM.

To build a dataset of natural motions for retrieval, this study generated a linear mixed effects statistical model (significance threshold of alpha being less than 0.05). This was chosen because there were multiple groupings in the dataset and involved repeated measurements of the same dog. This model would also give some predictive power instead of just a repeated measures ANOVA test, making it more useful for clinicians to apply in their practice. The p-values were based on the significance of the terms included.

RESULTS

Statistical analysis through a linear mixed effects model on the joint ROM and velocity determined joint condition, age, and breed group all can affect different parts of retrieval. The effect of different joint condition on knee deceleration ROM was significant. In addition the Lab mix group and Other breed group significantly differed in elbow acceleration ROM. Acceleration and deceleration strategies did not have any effect on the ROM. However, age did have a significant effect on elbow ROM during acceleration and the magnitude of the dog's horizontal velocity, verifying that this experimental method can yield expected results on known relationships.

Joint Condition Effect

The following table gives the measured ROM based on knee and elbow joint angles and velocities for a given breed group, joint condition and age. The appendix includes the statistical models and confidence intervals on each investigated scenario. Joint condition appears to have a significant effect on knee ROM during the deceleration phase across all dogs. Compromised dogs have smallest knee deceleration ROM in comparison with susceptible dogs and sound dogs ($p=0.017$, $p=0.02$ respectively). Sound dogs have a higher ROM than compromised dogs, but lower ROM than susceptible dogs. From Figure 3, there is a non-linear relationship between the joint condition of the dogs on both the knee and elbow ROM. Statistical analysis showed that age centered over all the data negatively impacted the elbow acceleration ROM ($p=0.0003$).

The response variables average shoulder velocity during the acceleration phase, elbow ROM, and knee ROM were also compared across different breed groups. The analysis did suggest that the Lab mixes and Other group had a higher elbow acceleration ROM than the Retriever group ($p=0.005$, $p=0.004$ respectively). The elbow deceleration ROM in the other breed group was also higher than the Retriever group ($p=0.002$). The Shepherd group had the highest mean shoulder velocity and elbow ROM across the groups. The Retriever group had the highest variability across in shoulder velocity and knee ROM. The elbow ROM for Lab mixes as seen from figure 4 below does not look significantly different from the Retriever group. However when analyzing the actual data points, it is clear a bifurcation happens in the lab mixes which is what is causing the effect of the breed group to appear significant.

Observation and Classification of Strategies

The dogs used three strategies used for accelerating after the toy, which were labeled as the Face Away, the Whip Around, and the By Command. The Face Away strategy had the dogs already facing the same direction as the toy was thrown and only once the toy was in the field of view that the dog accelerated. The Whip Around strategy had the dog facing the owner when the toy was tossed and their head and body followed the toy as the whipped around to accelerate after the toy. This strategy always had the toy in the field of view. The final strategy involved the dog sitting or standing by the owner's side and waited until a command before accelerating after the thrown toy. These three strategies are laid out in figure 5.

Likewise, four strategies for decelerating and picking up the toy were observed: the Pounce, the Skim Over, the Loop Back, and the Mid-air catch. The Pounce involved the dog decelerating in line with the toy and punching both forelimbs out onto the toy, pouncing on it. The Skim Over involved the dog running alongside the toy and trying to scoop it up as they ran passed. The Loop Back had the dog run past the toy and decelerate in an arc as it came back to the toy's position to pick it up. The final strategy used the mid-air catches, where the dog running in line with the toy would leap forward to catch the toy in mid-air. Depending on the height of the toy off the ground dog would either partial or entirely leave the ground. The dog would land hind limbs first with the knee's flexing to absorb the impact. If the dog only left the ground partially, then their forelimbs would leave and come back down, flexing knee and elbows at the impact. Figure 6 shows the four different strategies. When included in the statistical model, the elbow and knee ROM did not appear significantly impacted by the strategies the dog used for acceleration or decelerated ($p>0.05$).

Verification of an Expected Trend

As a control for the experimental method and data collection, the relationship between average shoulder velocity of each dog's acceleration and their age and was found to be significant ($p=0.003$). From figure 8, it is apparent that age is negatively correlated with velocity.

Inter-User Variability

Plots from the first investigation show remarkable similarity in tracing the dog's points across three independent trials. This provides some confidence in the reproducibility of the results for a single researcher. When compared to another researcher's tracking, there appears to be some conservation on the trend lines, however there is more random differences and variability. The linear mixed effects model for these data is in the appendix. However the model did demonstrate roughly 4 degrees difference on average in between users in figure 11. This indicates that, on average, there is not a large variability in how user 1 and user 2 track dogs. Additionally, the model demonstrated that, on average, the ROM increases as the dog accelerates from its first full stride to its third full stride as noted by the shape change in figure 11.

The second investigation determined with ANOVA that user did not significantly impact the ROM of the tracked videos, but that the stride type did significant impacted the ROM ($p=0.015$). Tukey's HSD test revealed that standing & running and standing & walking were significantly different. However, running & standing were not significantly different.

DISCUSSION

From this investigative study on dog retrieval acceleration and deceleration, the joint condition, age, breed group of the dog might have an effect on the range of motion (ROM) observed in the knee and elbow joints, and on the average horizontal shoulder velocity. However the variability within each subject, across dog breed groups, and the low subject number yield inconclusive evidence. This made it difficult to generate a highly predictive model, however the models described in the appendix are can estimate general averages among factors. Further and more precise predications would require follow up studies.

Since deceleration was previously uncharacterized, the finding that the deceleration of the knee and its ROM was affected joint condition gives new insight as to where symptoms of joint degeneration might be apparent. The fact that that this effect was only seen in knee not the elbow is potentially due to the weight distribution during deceleration. The forelimbs during deceleration take much of the force, and therefore there is a limited set motions which can accomplish the maneuver, making the elbow motion across decelerating dogs more uniform compared to the hind limbs. Hind limbs take a secondary role during deceleration and are freer from the kinematic constraint of impact braking force, therefore the difference in joint condition from dog to dog may be more apparent. Veterinarians already use the bunny hopping motion in the hind limbs during acceleration and deceleration as a diagnostic rule of thumb for dogs with hip and hind limb issues, so this supports that intuition. The fact that the knee acceleration study yielded no significant effects of joint condition on the knee could be explained by same theory. Since the hind limbs are generating most of the force during the acceleration phase, the motion in those limbs would be more uniform across dogs, while the elbows can demonstrate more variety implicit an each dog's motion. However, the effect was not seen in elbows during acceleration, even though it is known most of the force is generated in the hind limbs [3]. The effect may masked by the variability and noise in the low-powered data, so a more targeted study would be required to investigate this explanation further. However, a difference was seem among dog breed groups elbow ROM during acceleration. This could potential support the theory that differences among are more visible in the limbs acting in the supportive role to the limbs with the higher weight-bearing percentage. In other words, the variability of between the dogs' conditions would be apparent in the unloaded joints.

Further investigation about the factors age and mass might explain why certain dogs were prefer an acceleration and deceleration strategy over other. The most common strategy for the dogs were to Whip Around to accelerate and Pounce when decelerating, figure 13 and 14. Only high mass dogs would loop back, probably due to the higher momentum they generated. Figures 13 and 14 demonstrated that only younger dogs would decelerate through the Loop Back strategy, possibly due to their higher speeds. They were not able to slow down in time to catch the toy. The Whip Around strategy and Pounce strategies were predominately seen across all ages and masses. As the Whip Around strategy allowed the dog to keep the toy in the line of sight for the longest and the Pounce strategy is the simplest and most common capture strategy in hunting, these results should be expected for dog's participating in a modified hunting game. From figure 13, it is apparent that the older dogs generally frequently use Pounce which does require much less speed or coordination.

The effect of breed group on the observed ROM was limited to the difference between the Lab mix group and Other group from the Retriever group. Since both Lab mix and Other groups were different from the Retriever group, this analysis is picking up the contribution from the other breeds other than golden retrievers, Goldendoodles, and pure bred Labradors.

The investigations on intra-user and inter-user variability show a higher degree of variance within user when tracking across dogs that what would be comfortable. While, the second investigation did not find a significant difference between users, it also did not find a difference between dogs, which is concerning, since the main study indicated there may actually be differences. The standing data is of particular interest, as it is an indirect measure of user variability over time. These data points were collected on a motionless dog, but still showed roughly 10 degree difference, figure 12. Also walking and running did not show a significant difference which may indicate that researchers can get the same type of information from a dog just walking than retrieving. Since this particular investigation was very small, follow up on this lack of evidence is required.

From figure 11, there does not appear to be constant variance across dogs, which is an assumption in the first investigation's statistical model. This is why only general trends were reported and not significance values. That analysis, provided in the Appendix, showed a high standard deviation for the residual variability, indicating the knee ROM at least during acceleration is not a precise measurement. This does support the main study's finding with knee acceleration not being significantly impacted by other factors. It is just not a good place to find differences across dogs, joint conditions, or user tracking. These results also indicate that the residual variability, or variability within a subject's stride and within each user, is quite large compared to variability from one dog to another. Users in this tacking method may not be entirely consistent where they place a point.

Future Research Directions

Another noted feature of the dogs during acceleration was odd joint combinations that mirror each other. In some dogs, the acceleration step patterns is that the knee and wrist appeared to mirror each other's motion in a delayed wave pattern figure 15 (A). The mirroring is also seen but not to the same degree in the elbow and heel of the dog, figure 15 (B). This motion is more symmetric with less pronounced peaks. It is unclear why these points are paired as such, and not to the same joint level (i.e. wrist and heel, knee and elbow). In other dogs, the joint pairs mirrored were on the same joint level on different limbs, like in figure 16. The only shared characteristics between these dogs were that they were young and clinically sound. Due to the variability in the dogs' running patterns and with low sample numbers, it was difficult to distinguish trends or come up with potential explanations of this phenomena. However, it does propose a new direction for future kinematic studies on dog acceleration.

Technical Difficulties

As this study was purely investigative, the statistical analysis done acts as a scan for potential factors. The repeated models were not altered to prevent possible alpha level inflation. Follow up studies are required to further investigate whether these effects are truly significant. Also, while the age versus velocity model in figure 9 looks like a correlation coefficient could be calculated, there is no standardized method for that in mixed effects models and is an active area of research.

Due to time constraints and labor intensive video analysis, the study could not ascertain more variables and some of the collected information was not used. Recruitment of retrieving dogs proved to be challenging as the dogs had various levels of interest in retrieving. Also, while young dogs with joint issues are in the pet population, this study was not able to recruit any. So it was not able to comprehensively separate age from joint condition as variables in the responses. Targeted recruitment for various joint conditions over a smaller variety of dog breeds would be a potential follow up study. The automatic tracking feature in MaxTraq © was not able to track the running dogs in the videos due to the low resolution the images and speed of the animals. Therefore the manual tool was used on each video frame, accounting for much more time than initially estimated. However, the data it yielded was quite useable for this studies purpose. Improved camera quality may allow automation of the tracking data and would vastly improve efficiency. The variance could also be greatly reduced by ensuring the dogs at all times remained perpendicular to the camera, as occasionally they would be slightly angled (<20 degrees) with respect to the camera when accelerating or deceleration. This made it difficult to track the limbs spatially in 2D.

CONCLUSION

This investigative study determined that the joint condition can be visually measured during the deceleration of a dog's knee. It also determined that breeds can have significantly different range of motion in their elbows during acceleration and deceleration. The proof of concept for this method of tracking features was supported by the confirmation of seeing the expected decrease in speed as age increased. The intra-user variability appears to have some effect on the clarity of the trends and may potentially impact the significance effects seen in this study, however overall the trends were similar and within a single researcher, the tracking was highly conserved. This lends some confidence in the reproducibility of any one researcher's results. It is encouraging because if this method was refined it could be developed into a diagnostic tool for veterinary field to test if a recorded footage of a dog's retrieval demonstrates the speed, ROM and joint angle expected for the dog's age and supposed joint health.

Almost all small animal clinical veterinarians are treating dogs with arthritis and joint issues. By quantifying the stress joints go through during retrieval, it can help understand why wear on the joints happens, where it happens, and how it can be countered. This investigation mapped the retrieval motion over a variety of dogs. If parameters or situations can be found where a dog might be over-stressing a joint from exercise, veterinarians can suggest preventative measures or safer alternates. This would then impact the aging pet populations and make the later years of these companion animals more comfortable.

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BIBLIOGRAPHY

[1] Kim, S. E., S. C. Jones, D. D. Lewis, S. A. Banks, B. P. Conrad, and G. Tremolada. (2015). In-vivo three-dimensional knee kinematics during daily activities in dogs. *Journal of Orthopedic Research*, *33*(11), 1603-1610. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/jor.22927/pdf

[2] Gregersen, C. S., N. A. Silverton, and D. R. Carrier, (1998). External work and potential for elastic storage at the limb joints of running dogs. *Journal of Experimental Biology*, *201*(23), 3197-3210. Retrieved from http://jeb.biologists.org/content/jexbio/201/23/3197.full.pdf

[3] Walter, R. M., and D. R. Carrier, (2009). Rapid acceleration in dogs: ground forces and body posture dynamics. *Journal of Experimental Biology*, *212*(12), 1930-1939. Retrieved from http://jeb.biologists.org/content/212/12/1930.long

[4] Fu, Y. C. (2011). Evaluation of a three-dimensional kinematic model for canine gait analysis. *American Journal of Veterinary Research*, *72*(3), 416-417. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/20919895

[5] Gregersen, C. S., and D. R. Carrier, (2004). Gear ratios at the limb joints of jumping dogs. *Journal of Biomechanics, 37*(7), 1011-1018. Retrieved from http://www.jbiomech.com/article/S0021-9290(03)00437-8/pdf

[6] Lee, D. V. (2011). Effects of Grade and Mass Distribution on the mechanics of trotting in dogs. *Journal of Experimental Biology*, 214(3), 402-411. Retrieved from http://jeb.biologists.org/content/214/3/402

[7] Moore, E. J., S. E. Kim, S. A. Banks, A. Pozzi, J. D. Coggeshall, and S. C. Jones, (2016). Normal patellofemoral kinematic patterns during daily activities in dogs. *BMC Veterinary Research*, *12*. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5123255/pdf/12917_2016_Article_889.pdf

[8] Pfau, T., A. G. de Rivaz, S. Brighton, and R. Weller, (2011). Kinetics of jump landing in agility dogs. *Veterinary Journal*, *190*(2), 278-283. Retrieved from http://www.academia.edu/20616557/Kinetics_of_jump_landing_in_agility_dogs

[9] Newton, P. M., V. C. Mow, T. R. Gardner, J. A. Buckwalter, and J. P. Albright, (1997). The effect of lifelong exercise on canine articular cartilage. *American Journal of Sports Medicine*, *25*(3), 282-287. Retrieved from http://journals.sagepub.com/doi/abs/10.1177/036354659702500302?journalCode=ajsb

[10] Rubin, C. T., and L. E. Lanyon, (1982). Limb mechanics as a function of speed and gait - A study of functional strains in the radius and tibia of horses and dogs. *Journal of Experimental Biology*, *101*(DEC), 187-211. Retrieved from

http://jeb.biologists.org/content/101/1/187.long?utm_source=TrendMD&utm_medium=cpc&utm_campaign=J_Exp_Biol_TrendMD_0

[11] Bockstahler, B., A. Tichy, and P. Aigner, (2016). Compensatory load redistribution in Labrador retrievers when carrying different weights - a non-randomized prospective trial. *BMC Veterinary Research, 12*. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4897959/pdf/12917_2016_Article_715.pdf

[12] Chase K, D.F. Lawler, F.R. Adler, E.A. Ostrander, and K.G. Lark, (2004). Bilaterally Asymmetric Effects of Quantitative Trait Loci (QTLs): QTLs that affect Laxity in the Right versus Left Coxofemoral (Hip) Joints of the Dog (*Canis familiaris*). *American Journal of Medical Genetic A.*, no. 124A, issue 3, pp. 239-247.

[13] Chase K, D. Carrier, K.G. Lark, D.F. Lawler, (2005). Genetic Regulation of Osteoarthritis: A QTL Regulating Cranial and Caudal Acetabular Osteophyte Formation in the Hip Joint of the Dog (*Canis familiaris*). *American Journal of Medical Genetic A.*, no. 135, issue 3, pp. 334-335.

[14] Feeney, L. C., C. F. Lin, D. J. Marcellin-Little, A. R. Tate, R. M. Queen, and B. Yu, (2007). Validation of two-dimensional kinematic analysis of walk and sit-to-stand motions in dogs. *American Journal of Veterinary Research*, *68*(3), 277-282. Retrieved from https://avmajournals.avma.org/doi/pdf/10.2460/ajvr.68.3.277

[15] Yoshikawa, T., S. Mori, A. J. Santiesteban, T. C. Sun, E. Hafstad, and J. Chen, (1994). The effects of muscle Fatigue on bone strain. *Journal of Experimental Biology, 188*, 217-233. Retrieved from http://jeb.biologists.org/content/188/1/217.short

[16] Biewener, A. A., and J. E. A. Bertram, (1993). Skeletal strain patterns in relation to exercise training during growth. *Journal of Experimental Biology*, *185*, 51-69. Retrieved from http://jeb.biologists.org/content/185/1/51.long?utm_source=TrendMD&utm_medium=cpc&utm_campaign=J_Exp_Biol_TrendMD_0

[17] Buckwalter, J. A. (1995). Osteoarthritis and articularcartilage use, disuse, and abuse – experimental studies. *Journal of Rheumatology*, *22*, 13-15. Retrieved from https://www.researchgate.net/publication/15447309_Osteoarthritis_and_articular_cartilage_use_disuse_and_abuse_Experimental_studies

[18] Yasuda, K., and K. Hayashi, (1999). Changes in biomechanical properties of tendons and ligaments from joint disuse. *Osteoarthritis and Cartilage*, *7*(1), 122-129. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/10367020

[19] Ragetly, C. A., D. J. Griffon, M. K. I. Hsu, L. M. Klump, and E. T. Hsiao-Wecksler, (2012). Kinetic and kinematic analysis of the right hind limb during trotting on a

treadmill in Labrador Retrievers presumed predisposed or not predisposed to cranial cruciate ligament disease. *American Journal of Veterinary Research*, *73*(8), 1171-1177. Retrieved from https://avmajournals.avma.org/doi/pdf/10.2460/ajvr.73.8.1171

[20] Chase K, P. Jones, A. Martin, E.A. Ostrander, and K.G. Lark, (2009). Genetic Mapping of phenotypes: disease frequency as a breed characteristic. *Journal of Hereditary*, no. 100, sup.1, pp. 37-41.

[21] Lawler, D. (2012). Pedigree Dog "Exposed": A Documentary. *Journal of Applied Animal Welfare Science*, vol. 15, p.181-185.

[22] "Elbow Dysplasia Trends" (2018). *Orthopedic Foundation of Animals*. Retrieved from https://www.ofa.org/diseases/elbow-dysplasia.

Table 1. Acceleration and deceleration phase ROM (degrees) for each grouping of dog. These abbreviations are employed: E-Elbow, K-Knee, and V-Average shoulder velocity (in/s) during the acceleration phase in a given trial. Column J indicates joint condition: s-sound, m-susceptible, c-compromised. Breed group is labeled Retr- Retriever group, Shep- shepherd mix group, Lab- Lab mix group, and Other- Other group.

Breed	Age (yrs)	J	n	K Accel ROM avg	K Accel ROM range	E Accel ROM avg	E Accel ROM range	K Decel ROM avg	K Decel ROM range	E Decel ROM avg	E Decel ROM range	V Avg (in/s)	V range (in/s)
Retr	≤ 7	s	4	60.20	38.1-75.7	71.91	58.6-89.3	95.53	59.0-74.3	59.82	48.9-74.1	194.4	152.0-271.6
Retr	≤ 7	m	2	64.20	56.7-80.9	82.08	63.8-69.9	70.28	56.3-87.1	59.50	74.3-77.1	260.1	216.6-292.0
Retr	≤ 7	c	0	-	-	-	-	-	-	-	-	-	-
Retr	>7	s	1	57.23	51.1-62.3	65.97	63.8-69.9	75.7	38.5-65.3	51.90	74.3-77.1	159.8	150.7-171.8
Retr	>7	m	0	-	-	-	-	-	-	-	-	-	-
Retr	>7	c	3	52.70	36.4-78.2	66.76	51.4-76.2	56.08	33.7-83.7	63.59	40.6-78.2	132.8	53.7-223.1
Shep	≤ 7	s	2	53.33	49.6-56.4	83.73	73.8-91.4	61.77	55.6-71.6	69.25	55.6-79.8	263.2	212.5-326.4
Shep	≤ 7	m	0	-	-	-	-	-	-	-	-	-	-
Shep	≤ 7	c	0	-	-	-	-	-	-	-	-	-	-
Shep	>7	s	0	-	-	-	-	-	-	-	-	-	-
Shep	>7	m	0	-	-	-	-	-	-	-	-	-	-
Shep	>7	c	0	-	-	-	-	-	-	-	-	-	-
Lab	≤ 7	s	2	49.5	33.8-65.5	88.68	63.4 -103.5	60.68	36.5-78.5	61.63	58-66.6	228.5	166.7-279.4
Lab	≤ 7	m	0	-	-	-	-	-	-	-	-	-	-
Lab	≤ 7	c	0	-	-	-	-	-	-	-	-	-	-
Lab	>7	s	1	41.6	30.6-49.2	62.37	50.4-71.3	61.95	53.2-70.7	69.57	58.6-76.5	194.5	187.9-196.3
Lab	>7	m	0	-	-	-	-	-	-	-	-	-	-
Lab	>7	c	0	-	-	-	-	-	-	-	-	-	-
Other	≤ 7	s	2	51.27	25.8-60.4	81.68	72.5-92	63.43	49.9-73.9	81.20	75.0-89.4	179.0	148.1-201.6
Other	≤ 7	m	0	-	-	-	-	-	-	-	-	-	-
Other	≤ 7	c	0	-	-	-	-	-	-	-	-	-	-
Other	>7	s	1	55.30	44.3-62.9	71.77	72.5-92.0	69.80	67.3-74.0	71.6	75.0-89.4	193.1	167.5-216.4
Other	>7	m	1	59.57	57.4-61.3	83.40	79.7-86.7	68.07	67.4-68.4	71.13	65.8-74.5	221.3	188.7-203.6
Other	>7	c	0	-	-	-	-	-	-	-	-	-	-

Table 2. Summary of Subjects and their Background

Subject	Gender	Age (yrs)	Breed	Weight (lbs)	Exercise Levels	Joint Cond.	Type of Accel.	Type of Decel.
1	M	2.33	German Shepherd	80	moderate	Sound	face away	skim over/ loop back
2	M	5	Goldendoodle	100	mild	Sound	face away/ whip around	pounce
3	M	3.66	Golden Retriever	81	mild	Suscept.	command/ whip around	pounce/ loop back
4	F	5	Lab/Siberian Husky	70	moderate	Sound	whip around	midair/ skim over
5	M	2	Goldendoodle	55	moderate	Suscept	command	pounce
6	M	6	Siberian Husky	80	mild	Sound	face away	pounce
7	M	8	British Lab	65	intense	Sound	command	skim over/ pounce
9	F	6	Beagle	19	mild	Sound	whip around	pounce
10	F	10	Springer Spaniel mix	35	moderate	Suscept	whip around	midair
12	F	5	Shepherd mix	46	mild	Sound	face away	pounce
13	F	5	Lab/Mastiff mix	100	mild	Sound	face away	skim over/ loop back
14	F	10	Lab	80	none	Compr.	whip around	pounce
15	M	6	Goldendoodle	71.8	moderate	Sound	whip around	pounce
16	M	12	Goldendoodle	77.4	mild	Compr.	whip around/ face away	pounce
19	M	10	Draathar	70	none	Sound	command	skim over
20	F	3	Golden Retriever	85	mild	Sound	whip around	pounce
21	F	12	Lab/unknown	45	moderate	Sound	whip around	pounce
22	F	10	British Lab	84.6	mild	Compr.	face away	n/a

FIGURES

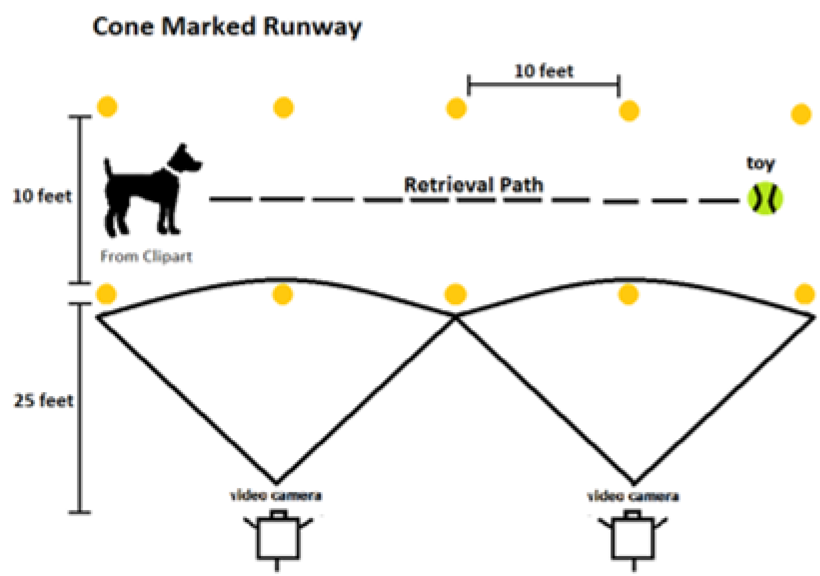
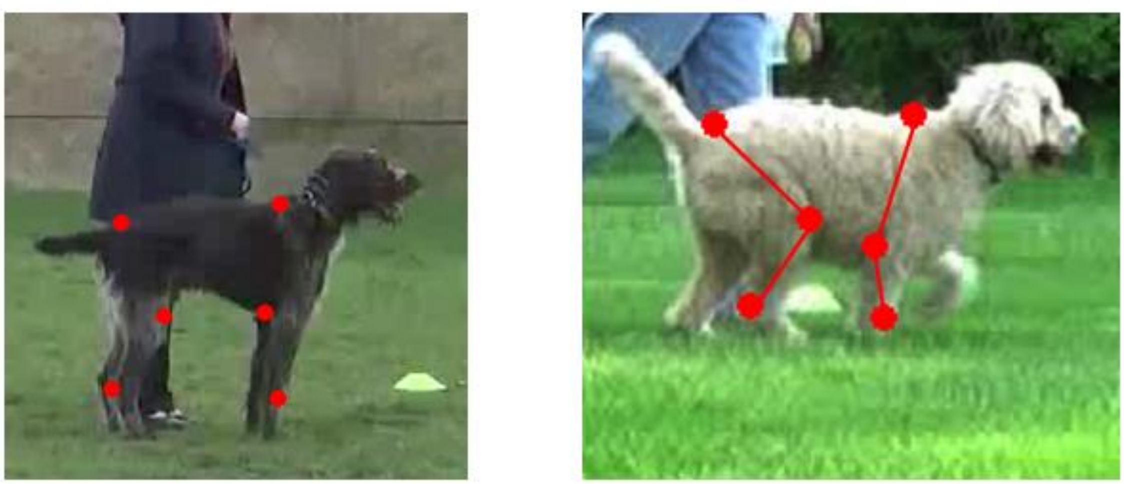


Figure 1. This is the trial setup and spacing for a generic subject's retrieval. It also shows how the video cameras were placed to capture the acceleration phase (left camera) and deceleration phase (right camera).



(A) (B)

Figure 2. Display of the standing and accelerating position of two subjects and the tracked locations (red dots). The lines on frame (B) indicate the points used for each joint angle value.

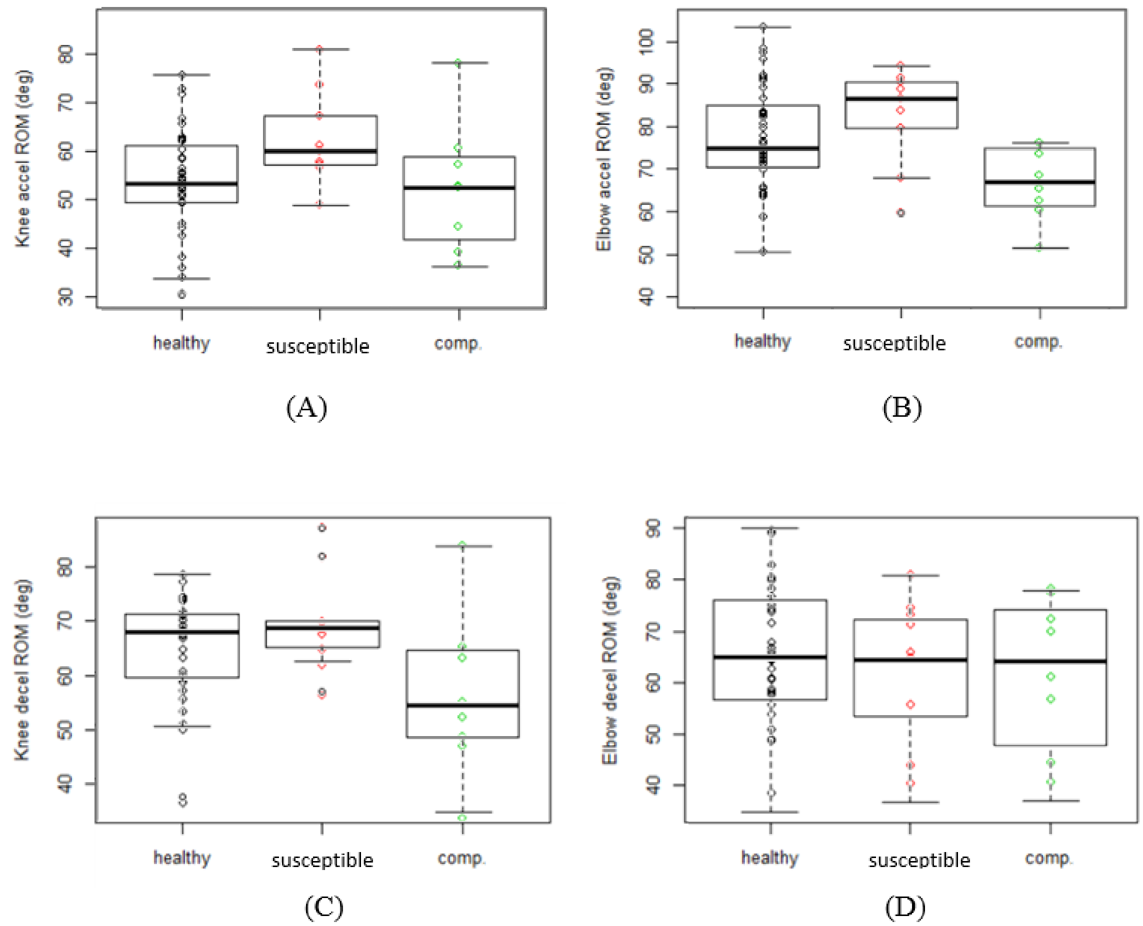


Figure 3. This plots the maximum ROM (deg) seen in each trial portion against the specified joint condition of the dog. (A) and (B) are on the acceleration phase of the retrieval. (C) and (D) are on the deceleration phase of the retrieval. There is a non-linear relationship between joint condition categories, however (C) exhibit a significant difference in ROM across categories.

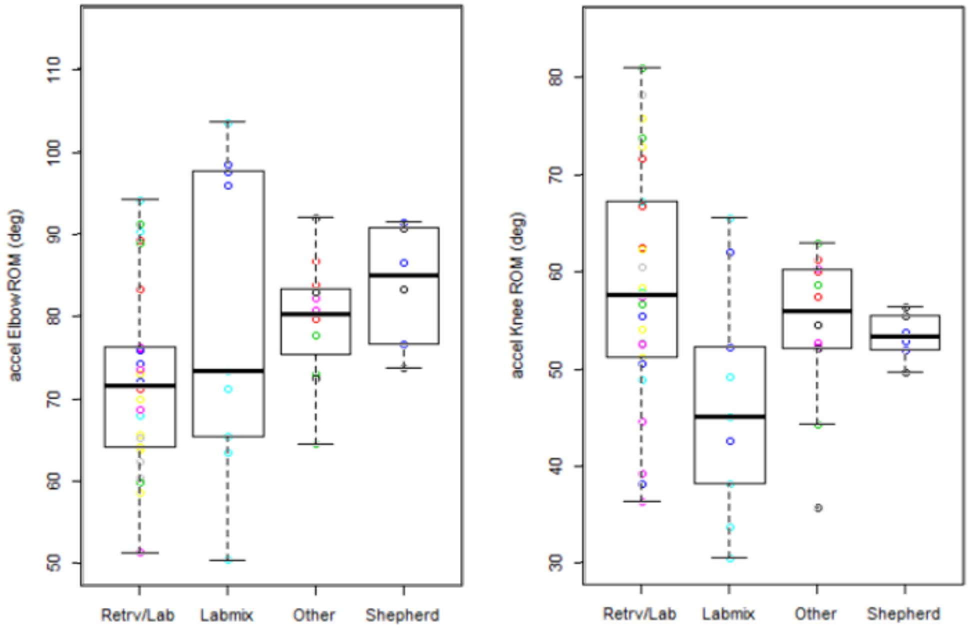


Figure 4. This showed the distribution of ROM measurements observed in different breed groups during the acceleration phase. Similar colors indicate the same dog.

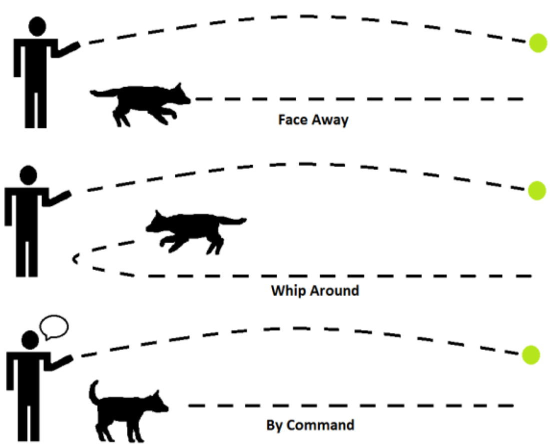


Figure 5. Simple diagrams of the three acceleration strategies. The Face Away strategy is used by a dog when it waits for the toy to appear in its line of sight. The Whip Around strategy is used when the dog wants to keep the toy in its line of sight even while it is being tossed. The By Command strategy is when the dog waits for a command before pursuing the toy.

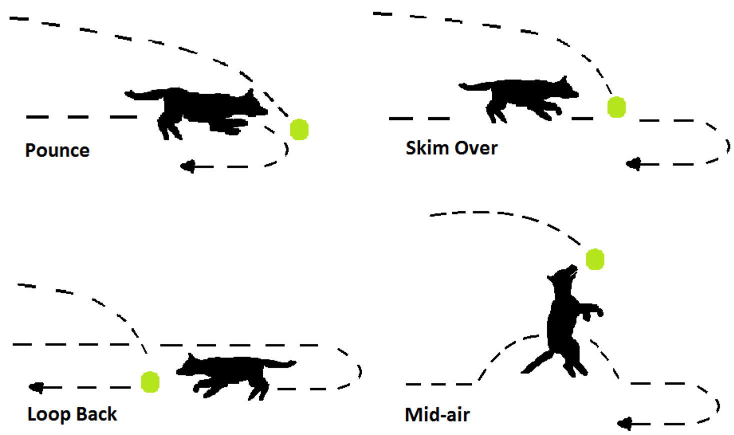


Figure 6. Simple diagram of the four different deceleration strategies. The Pounce strategy maximizes precision and is the most natural hunting behavior. The Skim Over strategy picks up the toy as the dog runs by due to either the speed of the dog or extending the deceleration period. The Loop Back strategy requires less coordination and speed but still extends deceleration. The Mid-air catch uses the most coordination skills and has the most impact on the joints.

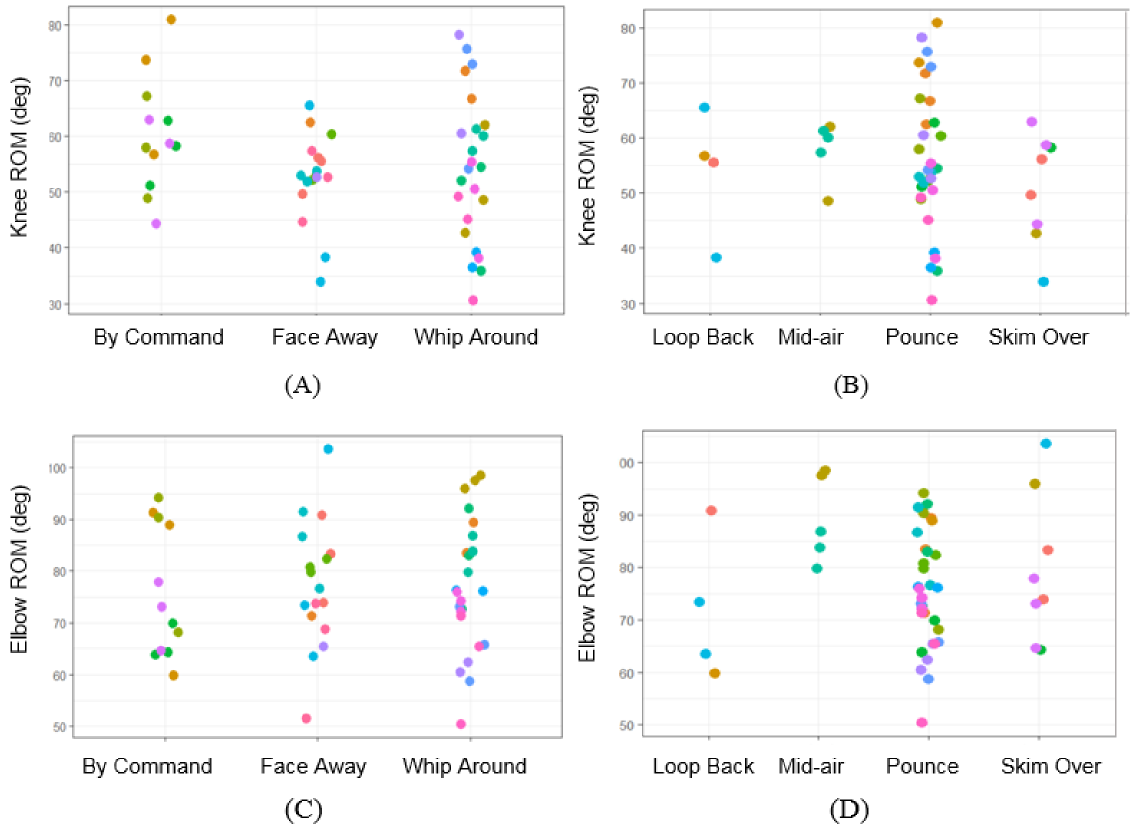


Figure 7. This plots the span of observed knee ROM in the acceleration phase (A) and the deceleration phase (B). The lower plots show the span of observed elbow ROMs in the acceleration phase (C) and the deceleration phase (D). Similar colors on the figures indicate the same dog.

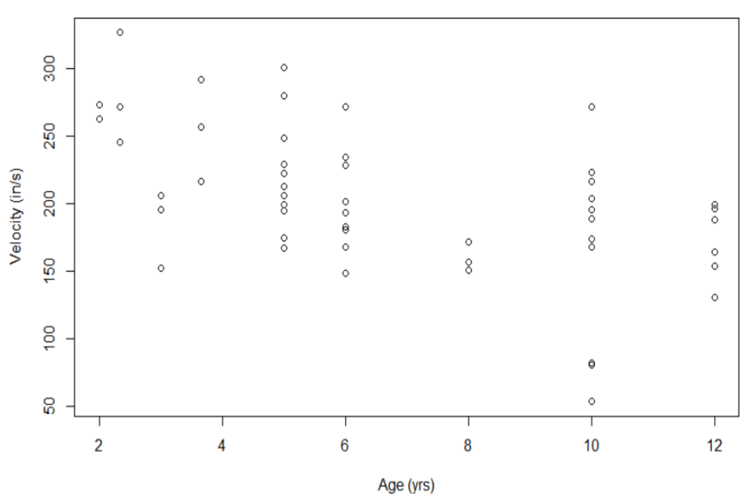
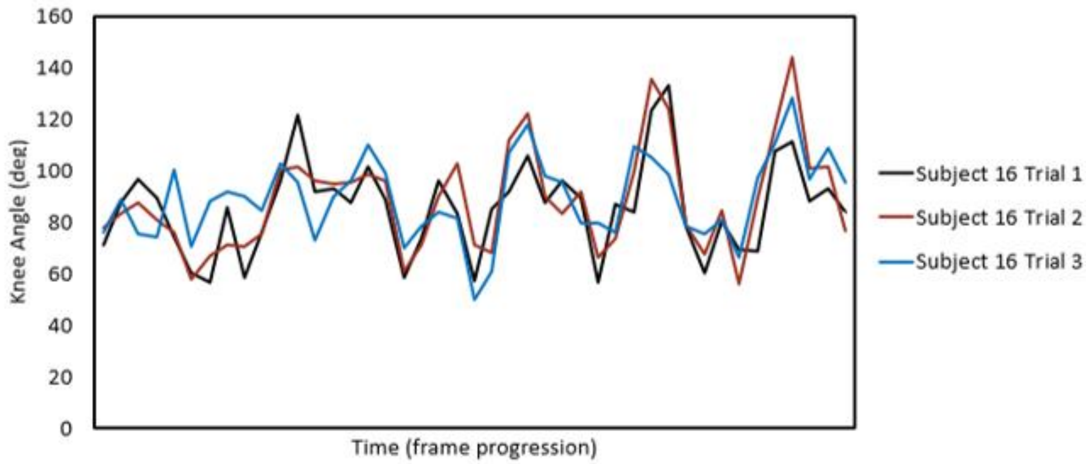
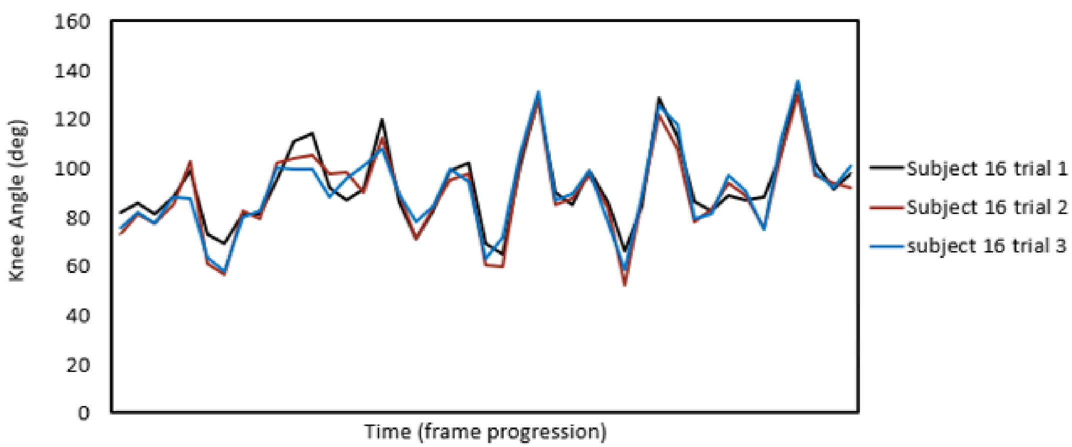


Figure 8. This plots the average shoulder velocity across all the dogs’ trials versus age.



(A)



(B)

Figure 9. Each frame demonstrates the variability within a single user on independent tracking replications of the same video. Frames (A) and (B) are tracked trials of the two researchers for side by side comparison.

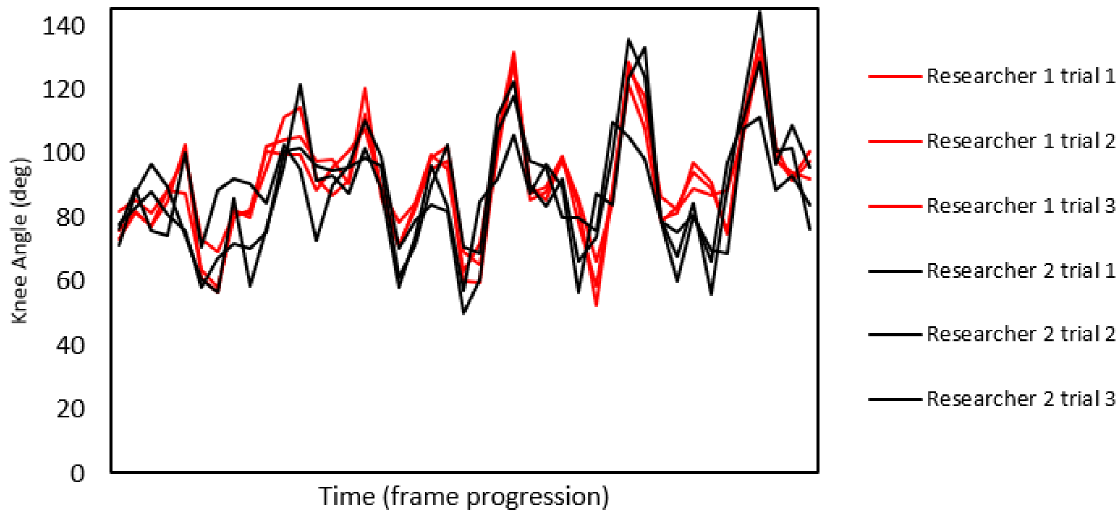


Figure 10. An overlay of two users' repeated tracks on the same video.

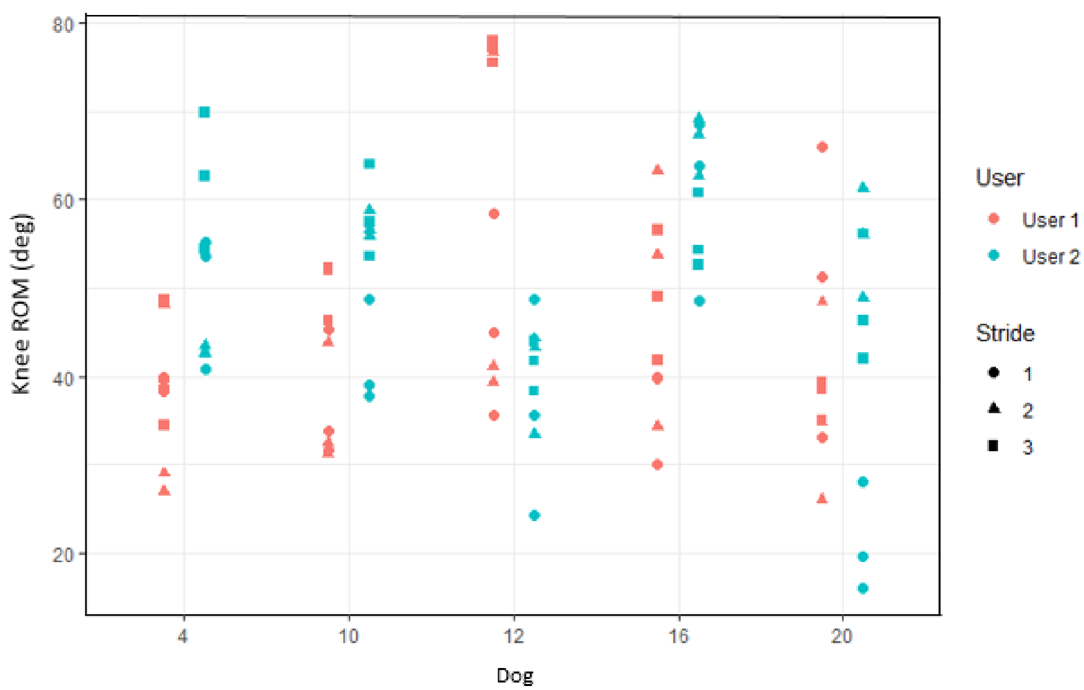


Figure 11. This demonstrates a side by side comparison of all the videos data collected in this small investigation. The columns are grouped by dog and the color indicates which user measured that ROM (deg). The shape indicates whether it was the first, second, or third full accelerating stride.

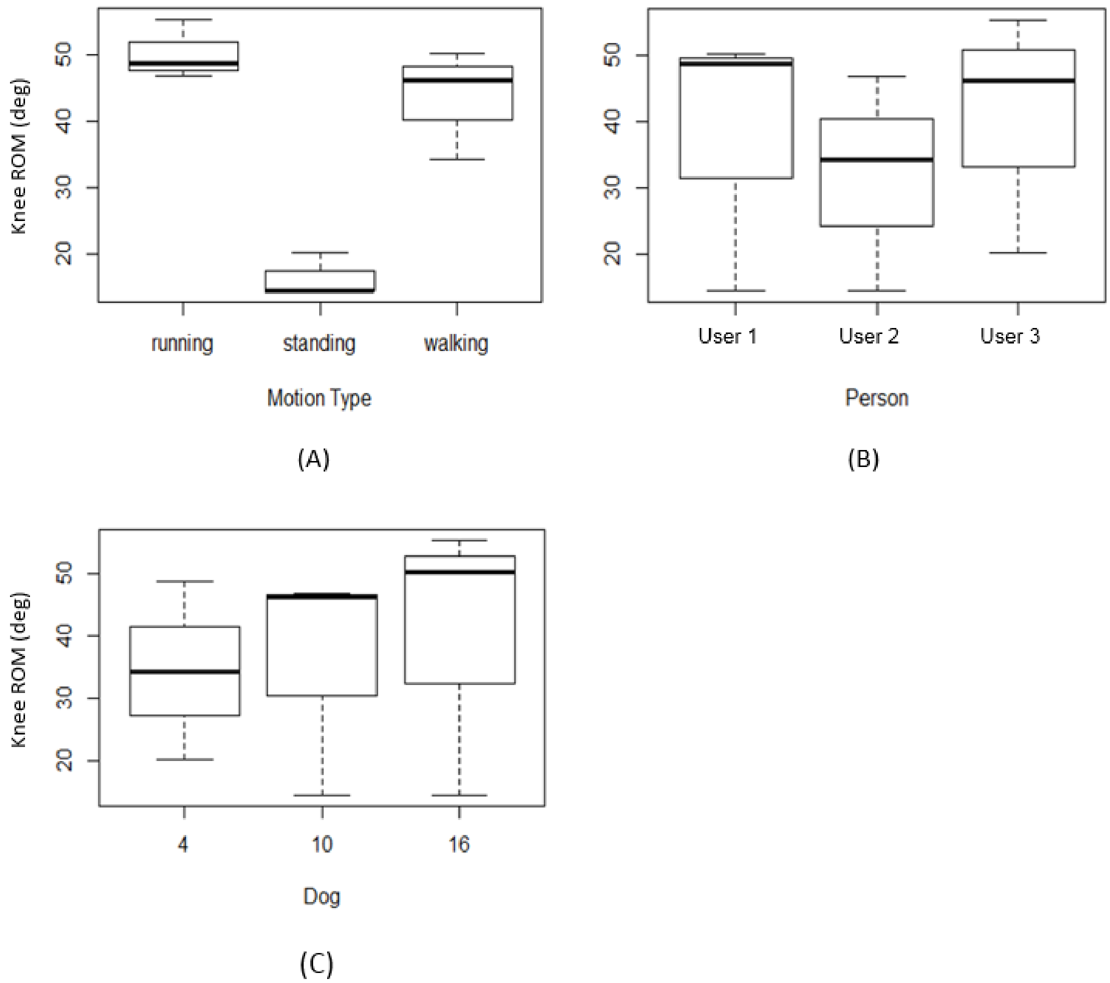
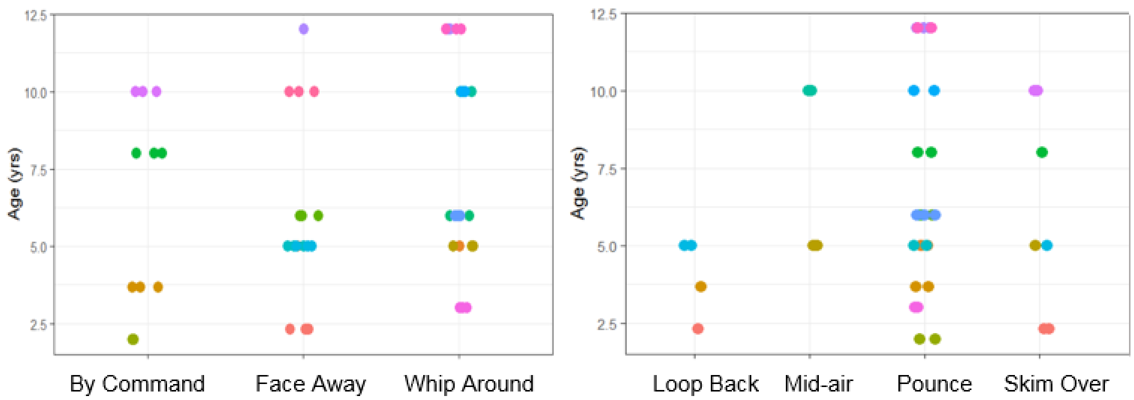
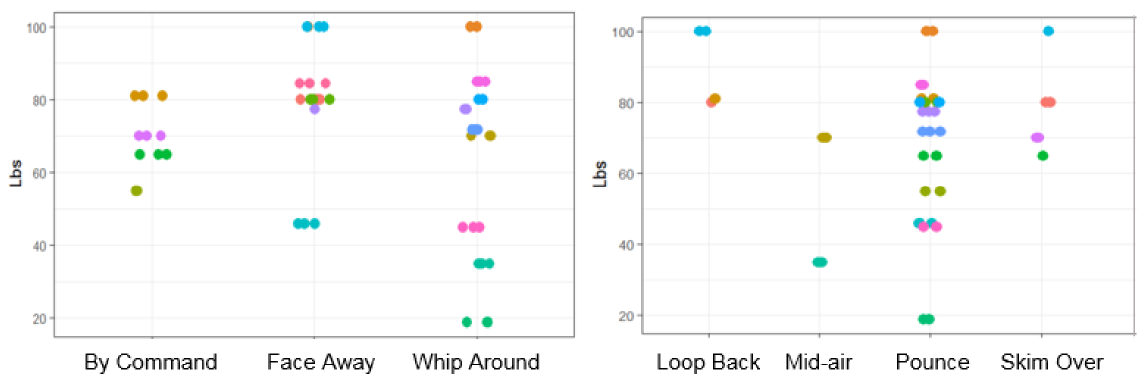


Figure 12. This displays the spreads of knee ROM (deg) across the different stride types and the blocks in the Latin Square design: Users and Dog. This can show overall spreads but neglects to show the combination of groups' effects on knee ROM, as an example it does not show where the running ROM versus standing ROM start and stop on dog 10 in panel (C).



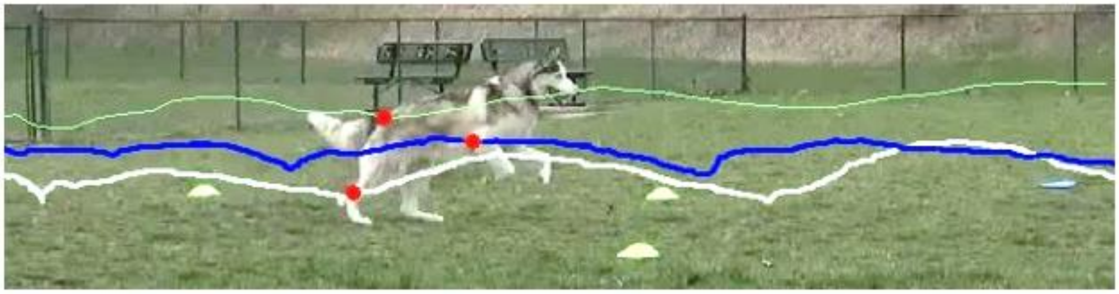
(A) (B)

Figure 13. This plots the age distribution of the different acceleration strategies (A) and the deceleration strategies (B).

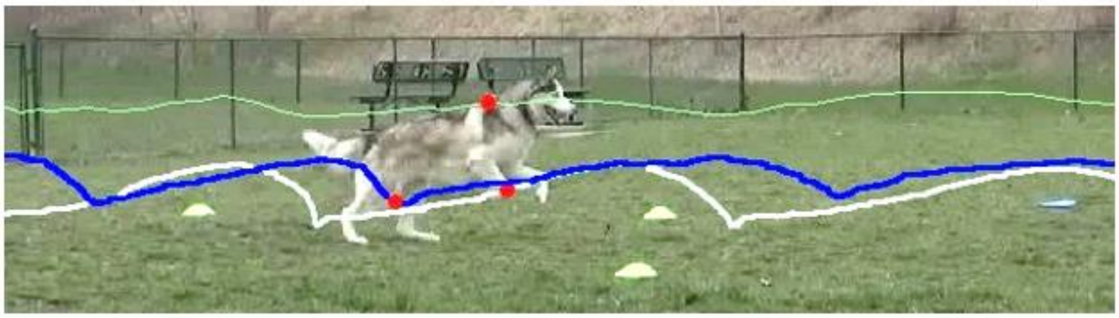


(A) (B)

Figure 14. This plots the mass distribution of the different acceleration strategies (A) and the deceleration strategies (B).

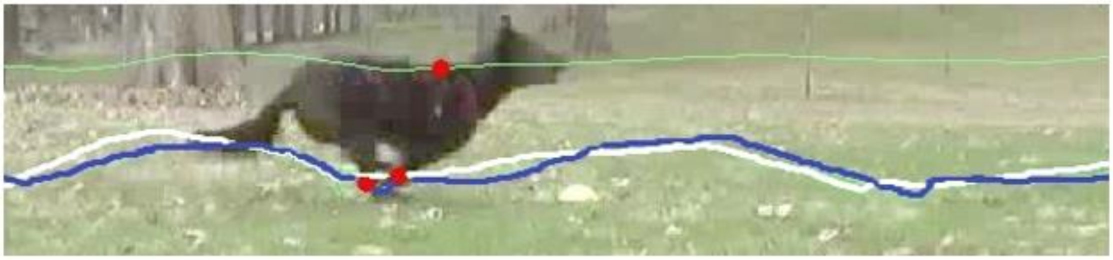


(A)

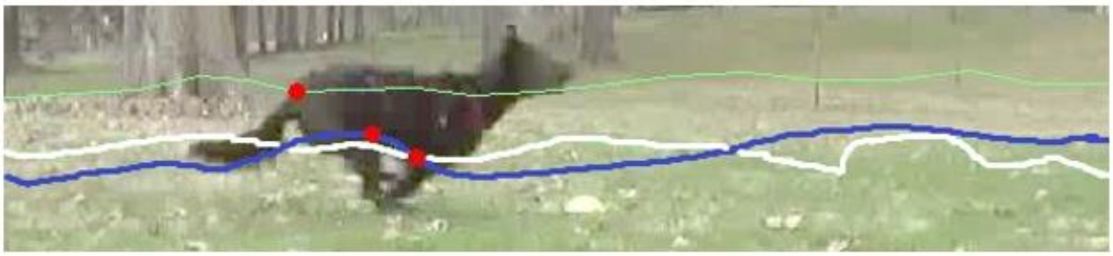


(B)

Figure 15. (A) Acceleration disjoint trail lines of tracked shoulder (green), knee (blue), wrist (white) points (red dots) on a subject. (B) Acceleration trail lines of tracked hip (green), elbow (blue), heel (white) points (red dots) on the same subject.



(A)



(B)

Figure 16. (A) Acceleration synchronized trail lines of tracked shoulder (green), wrist (white), heel (blue) points (red dots) on a different subject. (B) Acceleration trail lines of tracked hip (green), knee (blue), elbow (white) points (red dots) on the different subject.

APPENDIX

Below are tables on the statistical models for the elbow and knee acceleration and deceleration. The highlighted values show the significant variables for the response. The intercept term in the models is expected to be significant because it is the estimated mean ROM for the joint and retrieval phase. Also the ages of the dogs were centered for the models to provide interpretable intercepts terms. The terms in the models were included because they were suspected to potentially affect the ROM or velocity, according to visual analysis of the data. However, not all these terms proved to be significant.

Mixed Effects Linear Model Knee Acceleration

$$Knee\ ROM_i = \beta_0 + \beta_1(Joint\ Cond.)_i + \beta_2(Centered\ Age)_i + \beta_3(Breed\ Group)_i + \varepsilon_i$$

For this equation “i” indexes subject and the treatment is acceleration.

The calculated random effects within each subject was roughly a half of the variance observed across subjects (36.09, 83.38).

Factors	**P-value**	**Lower CI**	**Higher CI**
Intercept of average age of compromised Retriever group dog	<0.0001	38.153	61.588
Joint Condition (maybe)	0.073	-1.540	34.128
Joint Conditions (sound)	0.185	-5.102	26.475
Centered Age	0.578	-1.274	2.283
Breed group (Lab mix)	0.024	-26.756	3.498
Breed group (Other)	0.169	-20.007	7.319
Breed group (Shepherd)	0.408	-19.143	7.780

Mixed Effects Linear Model Elbow Acceleration

$$Elbow\ ROM_i = \beta_0 + \beta_1(Joint\ Cond.)_i + \beta_2(Centered\ Age)_i + \beta_3(Breed\ Group)_i + \varepsilon_i$$

For this equation “i” indexes subject and the treatment is acceleration.

The calculated random effects within each subject was roughly a fifth of the variance observed across subjects (8.183, 93.90).

Factors	**P-value**	**Lower CI**	**Higher CI**
Intercept of average age of compromised Retriever group dog	<0.0001	67.934	86.631
Joint Condition (maybe)	0.657	-17.320	10.923
Joint Conditions (sound)	0.130	-22.196	2.850
Centered Age	0.0003	-3.977	-1.179
Breed group (Lab mix)	0.005	4.085	23.671
Breed group (Other)	0.004	4.460	22.941
Breed group (Shepherd)	0.127	-2.338	18.827

Mixed Effects Linear Model Knee Deceleration

$$Knee\ ROM_i = \beta_0 + \beta_1(Joint\ Cond.)_i + \beta_2(Centered\ Age)_i + \beta_3(Breed\ Group)_i + \varepsilon_i$$

For this equation “i” indexes subject and the treatment is deceleration.
The calculated random effects within each subject was roughly a fourth of the variance observed across subjects (14.72, 97.32).

Factors	**P-value**	**Lower CI**	**Higher CI**
Intercept of average age of compromised Retriever group dog	<0.0001	42.668	63.489
Joint Condition (maybe)	0.017	3.437	35.233
Joint Conditions (sound)	0.020	2.667	31.536
Centered Age	0.398	-0.923	2.325
Breed group (Lab mix)	0.103	-20.423	1.870
Breed group (Other)	0.312	-16.022	5.120
Breed group (Shepherd)	0.295	-18.021	5.480

Mixed Effects Linear Model Elbow Deceleration

$$Elbow\ ROM_i = \beta_0 + \beta_1(Joint\ Cond.)_i + \beta_2(Centered\ Age)_i + \beta_3(Breed\ Group)_i + \beta_4(Decel.Type)_i + \varepsilon_i$$

For this equation “i” indexes subject and the treatment is deceleration.

The calculated random effects within each subject was a less than half the variance observed across subjects (60.54, 87.43).

Factors	**P-value**	**Lower CI**	**Higher CI**
Intercept of average age of compromised Retriever group dog who does Mid-air catches	<0.0001	35.235	83.449
Joint Condition (maybe)	0.409	-33.901	13.814
Joint Conditions (sound)	0.328	-31.964	10.673
Centered Age	0.270	-3.394	0.947
Breed group (Lab mix)	0.177	-5.239	28.403
Breed group (Other)	0.002	8.418	38.544
Breed group (Shepherd)	0.233	-6.569	26.942
Decel type (Pounce)	0.755	-15.64	21.568
Decel type (Skim Over)	0.392	-9.480	24.187
Decel type (Loop Back)	0.375	-8.900	23.635

Velocity Model

$$Horizontal\ Velocity_i = \beta_0 + + \beta_1(Centered\ Age)_i + \varepsilon_i$$

For this equation “i” indexes subject and the treatment is acceleration.

The calculated random effects within each subject was a more than double the variance observed across subjects (1505.6, 759.1).

Factors	**P-value**	**Lower CI**	**Higher CI**
Intercept of average dog at average of age 6.72 yrs	<0.0001	184.474	223.366
Centered Age	0.003	-15.56	-3.184

Statistical Model for First User Variability Investigation

These terms were categorical as true or false in the data that generated this model.

$$Knee\ ROM_{ijk} = \beta_{0ij} + \beta_{1ij}(user\ 1)_{ij} + \beta_{2ij}(stride\ 2)_{ijk} + \beta_{3ij}(stride\ 3)_{ijk} + \varepsilon_{ijk}$$

The following is the fitted estimates for the model that R studio provided.

$$Knee\ ROM_{ijk} = 44.032 + -4.291(user\ 1)_{ij} + 5.293(stride\ 2)_{ijk} + 10.150\ (stride\ 3)_{ijk} + \varepsilon_{ijk}$$

For these equations “i” indexes subject, “j” indicates which video replicate, and “k” indexes which strides in the video. The first equation representing linear mixed-effects model that was constructed to assess the variability among measurements taken by the same user, and additionally, whether there is a difference in average KROM measurements taken between users. The second equation representing the same linear mixed-effects model as before; however, this equation additionally shows the values that were calculated for out data set in R Studio. For example, the coefficient -4.291 indicates that, on average, User 1 tracked ROM values at 4.291 degrees lower than User 2. Additionally, the coefficient 5.293 indicates that, on average, stride 2 was tracked to be 5.293 degrees larger than stride 1 for each dog.

Material provided courtesy of Kyla Jarvis and her Independent Study on Canine Biomechanics.

Statistical Analysis for Second User Variability Investigation

ANOVA	Sum of Squares	Mean of Squares	F value	p-value
Dog	51.9	26	1.77	0.361
Person	119.3	59.7	4.068	0.197
Stride Type	1920.6	960.3	65.474	0.015
Residuals	29.3	14.7	-	-

Tukey HSD on Stride Type	diff	Adjusted p-value
Standing and Running	-33.79	0.0009
Person	-6.69	0.3900
Stride Type	27.09	0.0029

Material provided courtesy of Ariel Bohner, Taylor Frey, and Veronica Roberts as part of a class project.