Peak forelimb ground reaction forces experienced by dogs jumping from a simulated car boot

David Pardey[1] MSc, ACPAT, Gillian Tabor[1] MSc, ACPAT, James A. Oxley[2] MRes and Alison P. Wills[1*] PhD

[1]Animal Welfare Research and Knowledge Exchange Arena, Department of Animal and Agriculture, University Centre Hartpury, Hartpury, Gloucestershire, GL19 3BE, UK

[2]Independent researcher, Measham, Swadlincote, DE12 7LQ, UK

Please address correspondence to Dr A. P. Wills at Alison.Wills@Hartpury.ac.uk

This article has been accepted for publication in Veterinary Record, 2018 following peer review, and the Version of Record can be accessed online at http://dx.doi.org/10.1136/vr.104788

Abstract

Many dog owners allow their pets to jump out of a car boot, however, to date there has been no study that has investigated whether this places dogs at risk of injury. The aim of this study was to investigate the relationship between height and peak vertical ground reaction force (vGRF) in static start jumps. Fifteen healthy adult dogs performed three jumps from a platform that represented common vehicle boot sill heights (0.55m, 0.65m, 0.75m), landing on a single force platform. Kinetic data (Fx, Fy and Fz) were normalised for body weight and analysed via a one-way repeated analysis of variance (ANOVA) and pairwise post-hoc tests with a Bonferroni correction applied. There was a significant difference in peak forelimb vGRF between both the 0.55m (27.35 ±4.14N/Kg) and the 0.65m (30.84 ±3.66N/Kg) platform (p=0.001) and between the 0.65m and 0.75m (34.12 ±3.63N/Kg) platform (p=0.001). There was no significant difference in mediolateral or craniocaudal forces between the heights examined. These results suggest that allowing dogs to jump from bigger cars with a higher boot sill may result in augmented levels of loading on anatomical structures. Further research is required to investigate the kinematic effects of height on static jump down and how peak forelimb vGRF relates to anatomical loading and subsequent injury risk.

Introduction

The percentage of households in the UK with pet dogs is estimated to be 24%, with a population of around 8.5 million [1]. There are many reasons why a dog will leave the home (trip to local park, vet visits, holidays, day boarding, attending competitions or shows) which usually necessitate vehicular transportation. UK legislation stipulates that dogs must be restrained when travelling in a vehicle [2], both for the driver and dog's safety. In addition, published guidance to handlers outlines specific environmental requirements when transporting a dog in a vehicle [3, 4], yet neither provides direction on appropriate methods of entry or exit into the back seat or rear compartment (boot); the areas in which many owners confine their dogs [5]. Techniques vary from manual lifting, allowing the dog to jump in and out, or employing the use of a ramp. However, no studies currently exist that investigate the reasons to opt for a particular method or the frequency with which each is used.

Lifting a dog can pose a risk of injury to both the owner and dog, dependent on the technique used. For example, lifting an animate and unpredictable object (such as a dog, weighing up to 50 kilograms) scores highly in a workplace manual handling risk assessment particularly when twisting/stooping postures are employed [6]. It is noteworthy that much evidence is available in the human field investigating the prevalence and risk factors associated with back pain [7–9], particularly in relation to lifting [6]. Guidance on the safe load limits when lifting has been published [6], and therefore, from a health and safety perspective lifting larger dogs should preferably be avoided.

With a wide variety of vehicle boot sill heights present in the UK [10], it is unclear whether these heights have a direct impact on the risk of injury. In allowing dogs to jump unaided out of vehicles, owners may be inadvertently predisposing their dogs to the development of musculoskeletal pathologies. Some studies have explored the biomechanics of competitive jump landings in dogs [11–14], however minimal quantitative canine studies investigating the effects of jump landing exist when investigating static start jump-downs. Given the paucity of research in this area, it is important to consider the biomechanical implications of jumping from a stationary position from a range of heights.

There are no studies of dogs that directly investigate the relationship between vertical ground reaction force (vGRF) and forelimb injury, however, equine studies have attempted to relate the action of jumping to the injury of three specific forelimb tendons [15]. Clear distinctions in loading were identified, with the highest peak loading occurring at the superficial digital flexor tendon (SDFT). Although the mechanical and functional properties of this tendon have been reported [16] and in vitro studies suggest the mechanisms of microtrauma [17, 18], no further clinical studies have been published for comparison. Out of the three jump heights investigated (0.8m, 1.0m and 1.2m), only the SDFT tendon absorbed substantially more force as height increased.

Evidence relating to peak vGRF experienced by dogs jumping from a static start would be of key interest to the veterinary profession in providing a clearer picture of the aetiology of common musculoskeletal pathologies (osteoarthritis, elbow dysplasia, hip dysplasia), where disease expression is reported to be affected by environmental variables [19]. If there is a significant effect of height on peak vGRF when dogs perform a static start jump, this would provide suitable evidence to recommend the use of prevention measures such as ramps.

Many studies have investigated the aetiology of conditions such as osteoarthritis (OA) [20–22] with many concluding that there are both normal and pathological adaptations of articular cartilage to joint loading. One study compared bone specimens of dogs with fragmented medial coronoid processes (FMCP) against those without (n=38) to demonstrate a significant relationship between fatigue micro-damage and FMCP [23]. Given that the repeated loading of bone leads to the formation of micro-cracks within mineralised tissue [24, 25], and with a paucity of specifically designed studies, it is plausible that elbow dysplasia could be partially a manifestation of repeated loading of the forelimbs when jumping from vehicles. It has been highlighted that increasing the load on ex-vivo elbow joints brings about significant changes in several joint space measurements [26].

Several studies have examined the kinematics and kinetics of dogs jumping over hurdles [11, 13, 27, 28], but not from a static start jump down. However, as jumps from a static start are commonly performed by dogs (from furniture, cars etc.), biomechanical studies are required to inform whether dogs should be allowed to perform these activities.

The aim of this study was to investigate the effect of height on peak forelimb vGRF when dogs perform a static start jump from a platform of equivalent height to a car boot. Heights were selected to represent a range of boot heights that exist in common car models. It was hypothesised that jumping from the higher platforms would result in increased peak vGRF due to the increased length of the aerial phase and the consequent change in downwards velocity (due to gravitational acceleration) at impact [13].

Materials and Methods

This study was approved by the ethics committee at University Centre, Hartpury and all work was conducted in line with institutional ethical guidelines. Fifteen dogs were recruited from a convenience sample through advertising at local agility clubs and dog walking groups. Information sheets were provided to owners along with a consent form. On receipt of signed consent forms, the medical history of each canine participant was requested (permission granted by owner) from their registered veterinarian. This enabled verification that participants met the inclusion criteria. Consent from owners was also gained verbally on the day at each stage of data collection once the research activity had been re-explained to them.

Immediately prior to data collection, each canine participant was physically assessed by the primary researcher (ACPAT Chartered Physiotherapist) to ensure that no contraindications to participation were present (e.g. lameness, musculoskeletal pain response, altered neurological state). All canine participants were visually gait assessed for a minute at walk and trot for soundness, together with spinal and peripheral limb palpation to exclude the presence of anatomical tenderness suggestive of pain. Knuckling testing was performed on all limbs since neurological deficit can affect gait parameters [29] and each peripheral joint (including the scapulothoracic articulation) was passively moved through the full range of motion to verify that no joint or soft tissue restrictions were present.

Inclusion and Exclusion Criteria

Dogs were excluded from the study if they were less than two years of age, as skeletal maturity of dogs occurs between the ages of 10 to 12 months and sexual maturity between seven and 21 months [30]. No upper age limit was set, however dogs were excluded if they had an underlying musculoskeletal pathology or undiagnosed lameness, since these are known to alter gait patterns [31–33] and may increase injury risk. Given this research necessitated subjects performing multiple jumps and additionally that ‘long and low' conformation can predispose to intervertebral disc extrusion [34, 35], chondrodystrophic breeds were excluded from the study. In line with other studies [11, 12], guidelines provided by the UK Kennel Club outlining specific dog height categories [36] in agility competition were utilised to inform the inclusion criteria, with consideration taken for the specification of the three jumping related obstacles (hurdle, table/pause box, hoop tyre). Given that dogs classed in the medium height category are not permitted to jump from heights higher than 0.45m, 0.40m and 0.55m for each of these obstacles respectively, only dogs with a leg length greater than 0.43m were included in the study. Although it is appreciated that dogs can be unpredictable, those without basic obedience skills (being able to sit and wait until told to move) were also not recruited.

Study Population

In order to account for potential sources of variation between dogs, baseline recording of breed, age, gender, weight (measured within the week of data collection) and forelimb length (measured from the distal phalanges to the top of the scapulae) were measured and documented. Nine breeds of dog and one mixed breed dog were recruited with ages ranging from two to nine years (mean 5.9 ± 2.39 years). Eight dogs and seven bitches were included of body mass ranging from 13.8 kg to 33.2 kg (mean 22.29 ± 5.26 kg). Forelimb length (measured to the withers) of the participants ranged between 0.45m and 0.68m (mean 0.57 ± 0.07m). Breeds included were Belgian Shepherd (4), Border Collie (3), Labrador Retriever (1), Flat Coated Retriever (1), Cocker Spaniel (1), English Springer Spaniel (1), Tibetan Terrier (1), Hungarian Vizsla (1), Bavarian Mountain Hound (1) and Crossbreed (1).

Jump Platform

A height adjustable, stable platform (0.9m by 1.1m) was constructed from a steel and aluminium alloy frame with a stiff medium-density fibreboard (MDF) top-board insert (Figure 1). Interchangeable platform leg lengths enabled three platform heights (0.55m, 0.65m and 0.75m) to be constructed. Setting 0.1m linear increments enabled representation of the spectrum of vehicle boot sill heights being investigated [10]. Non-slip rubber-backed carpeting was placed underneath and on top of the platform with their thicknesses taken into account to ensure the overall jump down heights were 0.55m, 0.65m and 0.75m.

Kinetic Data

The platform was positioned immediately in front of a single AMTI (Advanced Mechanical Technology Incorporated© MA, US) force plate of dimensions 400mm x 600mm so that vertical (Fz), craniocaudal (Fy) and mediolateral (Fx) forelimb landing ground reaction forces could be recorded. A capture rate of 500Hz and a time period of 10 seconds were used to ensure effective data collection [13]. Non-slip rubber matting was placed over the force plate and the surrounding area to ensure that dogs did not slip on landing. Two-dimensional video recording (Canon EOS 600D, 1280x720, 60fps) of each trial took place to enable confirmation of the validity of trials. The camera, mounted on a tripod, was positioned 3 metres immediately lateral to the force plate.

Experimental Protocol

In addition to the gait assessment, a five minute warm-up (walking and trotting) of each individual participant was performed to increase vascularisation and reduce transient joint stiffness [27]. Each dog was instructed by its owner to ascend a ramp onto the platform. As an acclimatisation procedure and individual pilot study, each dog was instructed to sit on top of the platform in a pre-determined start zone located towards the front edge of the platform, facing forwards towards the force plate. The dog was commanded to sit and stay while the owner positioned themselves four metres in front of the platform. The force plate was configured and armed, the video recording commenced and the researcher signalled to the owner to call their dog to jump off the platform.

A successful trial was classified as one in which the first limb to contact the ground (trailing limb) landed clearly within the rectangular target zone of the force plate. This was a rectangular area (outlined using masking tape, Figure 1.) denoting the position of the force plate. For all trials, both forelimbs contacted the force plate. Owing to variance in morphology and conformation, altered postures when jumping can occur between dogs [12]. Therefore, to ensure that the trailing forelimb landed consistently within the boundaries of the force plate, the jumping style of each dog required observation. If on the acclimatisation jump a dog did not land in the middle of the force plate, the platform was then moved forward or back in increments of 0.01m for a second acclimatisation jump [13]. The range of distances used was from 0.26m to 0.47m (mean 0.38 ±0.05). Once a successful trial was observed this counted as part of data collection and subsequent trials continued with the same configuration.

Dogs were required to complete three valid trials at each platform height. Comparable studies have recorded five trials [27], however given the nature of the experimental task and the height of the platforms, for ethical reasons only three trials were performed. The order in which a participant attempted the two lower platform heights was randomised and a five-minute break was scheduled between each trial in an attempt to remove any fatigue or potential cumulative joint loading effects. After the 0.55m and 0.65m platform trials, each subject was then considered for the 0.75m platform height trial. This third platform height was only permitted with explicit verbal consent of the owner and if the researcher was willing to proceed after observation of the individual dog's previous trials. It is appreciated that true randomisation in relation to the order of the three platform heights did not occur, however the method used was felt to be justified on ethical grounds.

Statistical Analysis

The kinetic data collected (mediolateral force (Fx), craniocaudal force (Fy) and vertical force (Fz)) were transferred to Microsoft® Excel® for Mac Version 14.5.3. Normalisation of ground reaction force (GRF) [37] by body mass (kg) was performed. A mean value of the three normalised peak GRF values (for Fx, Fy and Fz per platform height) was calculated for each dog (N/Kg). All data were analysed in SPSS Statistics (Version 23) To test for normality, a Kolmogorov-Smirnov Test was performed and data were found to be normally distributed (*p*>0.05). A one-way repeated measures analysis of variance (ANOVA) was used to test for statistically significant differences between the three heights. Post hoc testing was performed where significant differences were identified. Pairwise tests, with the Bonferroni adjustment were applied such that the criterion of significance was divided by the number of comparisons (3). Therefore a new criterion of significance ($p<0.017$) was applied to avoid spurious positive results [38].

Results

Following a physical assessment on each day of data collection, all 15 dogs recruited fulfilled the inclusion criteria and were eligible to participate. All dogs required no more than one acclimatisation jump in order to complete a successful trial. All fifteen dogs completed three trials at each of the platform heights. The distance between platform and force-plate that was set for each dog following a successful acclimatisation jump-down was recorded. In total, 135 successful jump-downs were recorded.

The first trial performed by subject one at the 0.55m platform was found to be invalid when retrospectively studying the raw data. Consequently, a mean value of the two subsequent valid trials completed by this dog, for this height, was calculated. All other 134 trials were valid and taken forward for analysis. An example of the GRF data for an individual subject can be seen in Figure 2. All peak limb forces reported are for pairs of forelimbs.

Vertical Ground Reaction Force (vGRF)

Peak forelimb vertical ground reaction forces (Fz) were significantly different between the different platform heights examined ($F_{(2,28)}=89.749$, $p = 0.001$, partial $\eta^2=0.865$; Figure 3). There was a significant difference ($p = 0.001$) in forelimb vGRF from 27.35 ±4.14N/Kg at platform height 0.55m to 30.84 ±3.66N/Kg at platform height 0.65m. From platform height 0.65m to 0.75m there was also a significant difference ($p = 0.001$) in vertical ground reaction force (Fz) from 30.84 ±3.66N/Kg to 34.12 ±3.63N/Kg. Between the 0.55m and 0.75m platforms a significant difference ($p = 0.001$) in vGRF was observed from 27.35 ±4.14N/Kg to 34.12 ±3.63N/Kg.

Craniocaudal Ground Reaction Forces (cGRF)

There was no significant difference in peak forelimb craniocaudal ground reaction forces (Fy) between the different platform heights examined ($F_{(2,28)}$=2.546, p=0.422, partial η^2=0.154).

Mediolateral Ground Reaction Forces (mGRF)

There was no significant difference in peak forelimb mediolateral ground reaction forces (Fx) between the different platform heights examined ($F_{(2,28)}$=0.947, p=0.400, partial η^2=0.063).

Discussion

Despite evidence of injuries occurring in dogs specifically participating in agility [39], little is known about the epidemiology of other canine sporting injuries [40]; a consequence most likely of the paucity of quantitative research available [41]. A range of sporting activities, including hunting [42], and greyhound racing [43], are yet to be fully investigated with preliminary data suggesting that dogs may be at risk of injury. Dogs are routinely transported in vehicles to participate in sports and complete their daily exercise routines, yet the effect of jumping out of a car boot is unknown. It is also worthy of note that dogs jumping from a vehicle may have undergone an extended period of recumbency meaning that they lack the warm up that is essential for injury prevention [44].

Results obtained in this study indicated that over three progressively increasing platform heights, peak forelimb vGRF significantly increased. There was a 12.8% increase from platform 0.55m to 0.65m and a 10.7% increase with a further 10cm rise in height. Overall, the peak forelimb vGRF from lowest to highest platforms increased by almost a quarter (24.80%).

To the authors' knowledge, this is the first canine study investigating the kinetics of a static start jump. However, these findings concur with previous research relating to jump height [13, 15] and illustrate that even a relatively small increase in jump-down height can significantly alter landing kinetics. However, it is worthy of note that the changes in peak vGRF were smaller in terms of percentage increase (12.8% (0.55m to 0.65m) and 10.7% (0.65m to 0.75m)) than the increase in jump down height, which was 18.18% for the 0.55m to 0.65m height and 15.38% for the 0.65m to 0.75m height. It would be expected that peak vGRF would be higher when jumping from the higher platforms due to the increased length of the aerial phase and the consequent change in downwards velocity (due to gravitational acceleration) at impact [13]. Jumping from a higher height could result in a steeper landing angle, which has been shown to correlate with increased peak vGRF and impulse in dogs jumping hurdles [13]. Considering this, peak vGRF increased comparatively less with increasing jump down height than might be expected.

Given that loading cadaveric forelimbs has resulted in significant changes ($p<0.05$) in humero-radio-ulnar congruency [26], particularly at 100% of bodyweight, it follows that when jumping down repeatedly from a vehicle boot, internal structures of the locomotor system are subject to increased loading. This might contribute to the higher risk of injury observed in agility dogs [39] who are transported frequently to training and competition events and to dogs who perform this task as part of their working role. In this study, the exclusion of dogs below 0.43m in height at the withers enhanced cohort homogeneity permitting more accurate comparisons. Further research should take place to confirm that these findings are consistent with smaller but equally popular breeds of dog. This could nevertheless be ethically problematic, given the known significant variance in temporospatial and kinetic variables between small and larger breeds [45].

The lack of any significant effect on mediolateral GRF seen in this study is perhaps a demonstration of the lack of variance in sagittal movement when landing on a perfectly level surface. Unlike cross-slope walking which can result in variability in mediolateral forces [46], dogs in this study were not required to markedly adapt to their landing conditions, given the force plate and rubber matting was level and stable. Furthermore, the dogs were not required to stop abruptly upon landing which would require more complex co-contraction of musculature [47] and increase the potential for multidirectional sway. There is a possibility that some dogs jumped slightly more to the left or right whilst still landing on the force plate. Further work is required to investigate jumping strategies in dogs and the effect of these on mediolateral forces. In addition, this study only reported peak mediolateral landing forces for paired limb contacts, which will not reflect that changes in body posture that occur throughout the duration of the stance period.

While most dogs were observed to continue to travel forwards under momentum, there was variance across subjects with some landing in an efficient manner, coming to a halt only one or two footfalls later. This variability may explain the insignificant findings (p=0.422) for the craniocaudal GRF data collected. In a domestic setting, both of these kinetic measures could vary if, for instance, a dog routinely jumps laterally away from a vehicle, perhaps towards the direction of a familiar building.

In this study, the highest mean peak vGRF was recorded to be 42.2N/Kg (at the 0.75m platform), which is directly comparable to the 45N/Kg vertical forces previously recorded of galloping dogs jumping over hurdles [13]. The forces sustained from a single jump in this study, therefore, have the potential to be withstood by the limbs, given that at gallop these forces can be exerted and absorbed during each galloping gait cycle [48]. In general, relatively few dogs jump hurdles or fences regularly, with those that do undertaking specific training techniques [39, 44]. Therefore, the comparable peak forelimb landing limb forces do suggest that consideration should be taken when allowing dogs to repeatedly jump from cars unaided.

This study did not attempt to investigate the consequences of vGRF on joints and soft tissues within the kinetic chain. As such, no evidence can be provided defining the relationship between the increased vGRF and potential injury. However, given the known variance in loading and viscoelastic properties of anatomical structures [49], failure will occur when loading limits are reached. This study only utilised healthy dogs, hence the data may not be applicable to all dogs, particularly those with pre-existing pathology that might affect their gait [50, 51].

One difference between the data collected in this study and jumping from cars is that some vehicles will have a raised boot sill relative to their compartment floor. In such circumstances, the dog would be performing a countermovement jump [52], albeit the ascension phase is relatively minimal. This could potentially reduce the landing distance, particularly given that there is no opportunity for significant momentum to be generated. Furthermore, the internal surface of a car boot (carpet, plastic) can differ in addition to the degree of damping offered by different landing surfaces which may impact on limb loading patterns [53].

Many of the previous canine studies examining jumping have used agility dogs as their sample population [12, 27]. This study, although including some dogs with agility experience, also included non-agility dogs, since it was believed this would improve applicability of the findings to the companion dog. While most dogs were able to follow instruction readily, it was observed that one or two non-agility dogs performed several trials before it was perceived they had been accustomed to the requirements of the task. Although this habituation effect witnessed by other authors [54, 55] occurred, it is likely that its effects were negligible, since the hesitancy shown by dogs was witnessed prior to their jump-down but did not appear to change the mechanics of the jump itself.

This study provides the first objective evidence to support the commonplace belief that allowing dogs to repeatedly jump clear from vehicles with high boot compartments may be inadvisable. However, further work is needed to definitively link increased peak forelimb vGRF to common canine forelimb pathologies. Although at present relevant authorities do publish guidance over the safe transportation of dogs [2–4], methods of entry and exit into or out of the vehicle are not explicitly outlined. It is hoped that this paper will increase the awareness of the potential for harm and promote positive changes in canine husbandry.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial or not for profit sectors. The authors would like to thank Mark Cox for his assistance with data collection and all the dog owners who kindly allowed their animals to participate in this study.

Figure Legends

Figure 1. Experimental set-up depicting the platform (0.9m x 1.1m) from which dogs performed a static start jump down and the force plate. The area of the force plate is indicated with tape on the rubber mat. The height of the platform was adjustable and was set to either 0.55, 0.65 or 0.75m. The distance (d) from the platform to the plate was dependent on the individual subject and the range of distances used was from 0.26m to 0.47m (mean 0.38 ±0.05).

Figure 2. Force plate data from one dog. All trials are shown for each jump down height (0.55, 0.65 and 0.75m) with the mean overlaid (solid line). Summed vertical forelimb landing forces (Fz) for pairs of limbs is shown in green, summed craniocaudal forelimb landing forces (Fy) is shown in red and summed peak mediolateral (Fx) forelimb landing forces is shown in blue.

Figure 3. Mean (of the three trials at each jump down height) peak vertical forelimb GRF (Fz) for all subjects. Lines represent the median and diamonds represent the mean.

References

1. PMFA (2017) Pet Population 2017. http://www.pfma.org.uk/pet-population-2017. Accessed 6 Oct, 2017
2. Department for Transport (2017) The Highway Code. https://www.gov.uk/browse/driving/highway-code-road-safety. Accessed 6 Oct, 2017
3. The KENNEL CLUB (2017) Road Travel with your Dog. https://www.thekennelclub.org.uk/media/8297/roadtravel.pdf. Accessed 6 Oct, 2017
4. RSPCA (2014) Transporting Dogs in Cars. https://www.rspca.org.uk/adviceandwelfare/pets/dogs/health. Accessed 6 Oct, 2017
5. RAC (2014) One in four motorists “break the law” by not restraining their dogs in the car. https://www.rac.co.uk/press-centre/press-releases/one-in-four-motorists-break-the-law-by-not-restra. Accessed 3 Nov, 2017
6. HSE (2012) Manual Handling at Work. http://www.hse.gov.uk/pubns/indg143.pdf. Accessed 6 Oct, 2017
7. HOY, D., BAIN, C., WILLIAMS, G., MARCH, L., BROOKS, P., BLYTH F., WOOLF, A., VOS, T., BUCHBINDER, R. (2012) A systematic review of the global prevalence of low back pain. Arthritis & Rheumatology 64, 2028–2037
8. WATERMAN, B. R., BELMONT, P. J., SCHOENFELD, A. J. (2012) Low back pain in the United States: incidence and risk factors for presentation in the emergency setting. The Spine Journal 12, 63–70
9. WONG, A. Y. L., KARPPINEN, J., SAMARTZIS, D. (2017) Low back pain in older adults: risk factors, management options and future directions. Scoliosis and Spinal Disorders 12,14
10. RICA (2017) Car Search. http://www.rica.org.uk/content/car-search. Accessed 6 Oct, 2017
11. BIRCH, E., CARTER, A., BOYD, J. (2016) An examination of jump kinematics in dogs over increasing hurdle heights. Comparative Exercise Physiology 12, 91–98

12. ALCOCK, J., BIRCH, E., BOYD, J. (2015) Effect of jumping style on the performance of large and medium elite agility dogs. Comparative Exercise Physiology 11, 145–150

13. PFAU, T., DE RIVAZ, A., G., BRIGHTON, S., WELLER, R. (2011) Kinetics of jump landing in agility dogs. The Veterinary Journal 190, 278–283

14. GREGERSEN, C. S., CARRIER, D. R. (2004) Gear ratios at the limb joints of jumping dogs. Journal of Biomechanics 37, 1011–1018

15. MEERSHOEK, L. S., SCHAMHARDT, H. C., ROEPSTORFF, L., JOHNSTON, C. (2001) Forelimb tendon loading during jump landings and the influence of fence height. Equine Veterinary Journal 33, 6–10

16. DOWLING, B. A., DART, A. J. (2005) Mechanical and functional properties of the equine superficial digital flexor tendon. The Veterinary Journal 170, 184–192

17. PATTERSON-KANE, J. C., PARRY, D. A. D., GOODSHIP, A. E., FIRTH, E. C. (1997) Exercise modifies the age-related change in crimp pattern in the core region of the equine superficial digital flexor tendon. New Zealand Veterinary Journal 45, 135–139

18. PATTERSON-KANE, J. C., WILSON, A. M., FIRTH, E. C., PARRY, D. A. D., GOODSHIP, A. E. (1998) Exercise-related alterations in crimp morphology in the central regions of superficial digital flexor tendons from young Thoroughbreds: a controlled study. Equine Veterinary Journal 30, 61–64

19. MICHELSEN, J. (2013) Canine elbow dysplasia: Aetiopathogenesis and current treatment recommendations. The Veterinary Journal 196, 12–19

20. CONCONI, M., HALILAJ, E., CASTELLI, V. P., CRISCO, J. J., (2014) Is early osteoarthritis associated with differences in joint congruence? Journal of Biomechanics 47, 3787–3793

21. HEIJINK, A., GOMOLL, A. H., MADRY, H., DROBNIČ, M., FILARDO, G., ESPREGUEIRA-MENDES J., VAN DIJK, C. N. (2012) Biomechanical considerations in the pathogenesis of osteoarthritis of the knee. Knee Surgery, Sports Traumatology, Arthroscopy 20, 423–435

22. TEICHTAHL, A. J., WLUKA, A. E., WIJETHILAKE, P., WANG Y., GHASEM-ZADEH, A., CICUTTINI, F. M., (2015) Wolff's law in action: a mechanism for early knee osteoarthritis. Arthritis Research & Therapy 17, 207

23. DANIELSON, K. C., FITZPATRICK, N., MUIR, P., MANLEY, P. A. (2006) Histomorphometry of fragmented medial coronoid process in dogs: a comparison of affected and normal coronoid processes. Veterinary Surgery 35, 501–509

24. BURR, D. B., TURNER, C. H., NAICK, P., FORWOOD, M. R., AMBROSIUS, W., HASAN, M. S., PIDAPARTI, R., (1998) Does microdamage accumulation affect the mechanical properties of bone? Journal of Biomechanics 31, 337–345

25. DANOVA, N. A., COLOPY, S. A., RADTKE, C. L., KALSCHEUR, V. L., MARKEL, M. D., VANDERBY, R., MCCABE, R. P., ESCARCEGA, A. J., MUIR, P. (2003) Degradation of bone structural properties by accumulation and coalescence of microcracks. Bone 33, 197–205

26. BURTON, N. J., WARREN-SMITH, C. M. R., ROPER, D. P., PARSONS, K. J. (2013) CT assessment of the influence of dynamic loading on physiological incongruency of the canine elbow. Journal of Small Animal Practice 54, 291–298

27. BIRCH, E., LÉSNIAK, K. (2013) Effect of fence height on joint angles of agility dogs. The Veterinary Journal 198, 99–102

28. CULLEN, K. L., DICKEY, J. P., BROWN, S. H. M., NYKAMP, S. G., BENT, L. R., THOMASON, J. J., MOENS, N. M. M. (2017) The magnitude of muscular activation of four canine forelimb muscles in dogs performing two agility-specific tasks. BMC Veterinary Research 13, 68

29. FOSS K., DA COSTA, R. C., RAJALA-SHULTZ, P. J., ALLEN, M. J. (2013) Force plate gait analysis in Doberman Pinschers with and without cervical spondylomyelopathy. Journal of Veterinary Internal Medicine 27:106–111

30. GEIGER, M., GENDRON, K., WILLMITZER, F., SÁNCHEZ-VILLAGRA, M. R. (2016) Unaltered sequence of dental, skeletal, and sexual maturity in domestic dogs compared to the wolf. Zoological

letters 2, 16

31. ABDELHADI, J., WEFSTAEDT, P., GALINDO-ZAMORA, V., ANDERS, A., NOLTE, I., SCHILLING, N. (2013) Load redistribution in walking and trotting Beagles with induced forelimb lameness. American Journal of Veterinary Research 74, 34–39

32. GORDON-EVANS, W. J., EVANS, R. B., KNAP, K. E., HILDRETH, J. M., PINEL, C. B., IMHOFF, D. J., CONZEMIUS, M. G. (2009) Characterization of spatiotemporal gait characteristics in clinically normal dogs and dogs with spinal cord disease. American Journal of Veterinary Research 70, 1444–1449

33. KAIJIMA, M., FOUTZ, T. L., MCCLENDON, R. W., BUDSBERG, S. C. (2012) Diagnosis of lameness in dogs by use of artificial neural networks and ground reaction forces obtained during gait analysis. American Journal of Veterinary Research 73, 973–978

34. PACKER, R. M. A., HENDRICKS, A., VOLK, H. A., Shihab, N. K., Burn, C. C. (2013) How long and low can you go? Effect of conformation on the risk of thoracolumbar intervertebral disc extrusion in domestic dogs. PLoS One 8, e69650

35. SMOLDERS, L. A., BERGKNUT, N., GRINWIS, G. C. M., HAGMAN R., LAGERSTEDT, A. S., HAZEWINKEL, H. A. W., TRYFONIDOU, M. A., MEIJ, B. P. (2013) Intervertebral disc degeneration in the dog. Part 2: chondrodystrophic and non-chondrodystrophic breeds. The Veterinary Journal 195, 292–299

36. THE KENNEL CLUB (2017) Agility course obstacles. https://www.thekennelclub.org.uk/activities/agility/new-to-agility/agility-course-obstacles/. Accessed 27 Oct, 2017

37. KROTSCHECK, U., TODHUNTER, R. J., NELSON, S. A., SUTTER, N. B., MOHAMMED, H. O. (2014) Precision and accuracy of ground reaction force normalization in a heterogeneous population of dogs. Veterinary Surgery 43, 437–445

38. FIELD, A. (2013) Discovering statistics using IBM SPSS statistics. Sage

39. LEVY, M., HALL, C. B., TRENTACOSTA, N., PERCIVAL, M. (2007) A survey of injuries occurring in dogs participating in agility. Clean Run

71–73

40. KERR, Z. Y., FIELDS, S., COMSTOCK, R. D. (2014) Epidemiology of injury among handlers and dogs competing in the sport of agility. Journal of Physical Activity and Health 11, 1032–1040

41. HAYES-DAVIES, D., (2014) Physiotherapy for the sporting dog. Companion Animal 19, 415–422

42. HOULTON, J. E. F. (2008) A survey of gundog lameness and injuries in Great Britain in the shooting seasons 2005/2006 and 2006/2007. Veterinary and Comparative Orthopaedics and Traumatology 21, 231–237

43. SICARD, G. K., SHORT, K., MANLEY, P. A. (1999) A survey of injuries at five greyhound racing tracks. Journal of Small Animal Practice 40, 428–432

44. BALTZER, W. (2012) Preventing injury in sporting dogs. Veterinary Medicine 107, 178–183

45. KIM, J., KAZMIERCZAK, K. A., BREUR, G. J. (2011) Comparison of temporospatial and kinetic variables of walking in small and large dogs on a pressure-sensing walkway. American Journal of Veterinary Research 72, 1171–1177

46. DAMAVANDI, M., DIXON, P. C., PEARSALL, D. J. (2012) Ground reaction force adaptations during cross-slope walking and running. Human Movement Science 31, 182–189

47. WILLAIMS, V. J., NAGAI, T., SELL, T. C., ABT, J. P., ROWE, R. S., MCGRAIL, M. A., LEPHART, S. M. (2016) Prediction of Dynamic Postural Stability During Single-Leg Jump Landings by Ankle and Knee Flexibility and Strength. Journal of Sport Rehabilitation 25, 266–272

48. WALTER, R. M., CARRIER, D. R. (2007) Ground forces applied by galloping dogs. Journal of Experimental Biology 210, 208–216

49. RADIN, E. L., PAUL, I. L. (1970) Does cartilage compliance reduce skeletal impact loads?. the relative force-attenuating properties of articular cartilage, synovial fluid, periarticular soft tissues and bone. Arthritis & Rheumatology 13, 139–144

50. BOCKSTAHLER, B. A., VOBORNIK, A., MÜLLER, M., PEHAM, C. (2009) Compensatory load redistribution in naturally occurring

osteoarthritis of the elbow joint and induced weight-bearing lameness of the forelimbs compared with clinically sound dogs. The Veterinary Journal 180, 202–212

51. RHODIN, M., BERGH, A., GUSTÅS, P., ÁLVAREZ, C. B. G., (2017) Inertial sensor-based system for lameness detection in trotting dogs with induced lameness. The Veterinary Journal 222, 54–59

52. AFIFI, M., HINRICHS, R. N. (2012) A mechanics comparison between landing from a countermovement jump and landing from stepping off a box. Journal of Applied Biomechanics 28, 1–9

53. CREVIER-DENOIX, N., POURCELOT, P., RAVARY, B., ROBIN, D., FALALA, S., UZEL, S., GRISON, A., VALETTE, J., DENOIX, J., CHATEAU, H. (2009) Influence of track surface on the equine superficial digital flexor tendon loading in two horses at high speed trot. Equine Veterinary Journal 41, 257–261

54. FANCHON, L., GRANDJEAN, D. (2009) Habituation of healthy dogs to treadmill trotting: repeatability assessment of vertical ground reaction force. Research in Veterinary Science 87, 135–139

55. GUSTÅS, P., PETTERSSON, K., HONKAVAARA, S., LAGERSTEDT., A. S., BYSTRÖM, A. (2016) Kinematic and spatiotemporal assessment of habituation to treadmill walking in Labrador retrievers. Acta Veterinaria Scandinavica 58, 87