Research Article

An examination of jump kinematics in dogs over increasing hurdle heights.

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Abstract

Research examining kinematic parameters of the canine athlete is markedly behind equivalent human and equine research. With increasing participation and popularity, canine sports science needs to bridge this gap with comparable equine research. The aim of this study was to examine changes to specific kinematic parameters as hurdle height increases. Twenty border collies and border collie crosses were analysed jumping over a single hurdle at increasing heights, starting with a pole on the floor and increasing to a maximum height of 65cm. Length of trajectory and jump speed were analysed, alongside apparent (without the use of markers) neck, lumbar spine and shoulder angles using Dartfish software. For each dog, the percentage of the hurdle height in relation to their height at the dorsal aspect of the scapula (withers) was used to normalise the dogs evenly.

Overall jump speed decreased as percentage height increased ($P < 0.001$), with a strong negative correlation between the two ($r = -0.815$). Length of trajectory significantly increased with percentage height ($P < 0.001$) with a strong positive correlation between the two ($r = 0.740$). However, length of trajectory decreased when a dog jumped $\geq$ 126% of its height to the withers. This is supported by a significantly more flexed apparent neck angle upon landing at this percentage height ($P < 0.001$). Apparent lumbar spine angles showed greater dorsal extension upon landing as percentage height increased ($P < 0.001$). Apparent shoulder angles become significantly more flexed as percentage height increased during the suspension phase of the jump ($P < 0.001$). These results suggest that dogs significantly alter their jump kinematics as hurdle height increases.

Keywords: Canine, Biomechanics, Jumping, Dartfish

Introduction

Despite the paucity of canine biomechanics research being identified almost a decade ago, there continues to be a distinct lack of research examining the canine athlete, particularly when compared to equivalent equine research (Colborne, 2007). Historically, equines have been the traditional sporting animal with research examining optimisation of athletic ability (Vogel, 1996) alongside identifying kinematic parameters that may be indicative of future success (Santamaria *et al*., 2002). This, in part, could be due to both the financial and time constraints attributed to producing a successful sporting horse, thus research examining ways to increase their competitive success is highly desirable.

Research in equine jump kinematics has determined that both fence height and fence type alters limb placement and joint angles during the take-off, suspension and landing phase of the jump (Clayton and Barlow, 1989; Powers and Harrison, 1999; Hole *et al*., 2002). An optimum take-off point has also been determined in horses, with 'good' show jumpers being better able to judge this optimum distance when compared to 'bad' show jumpers (Powers and Harrison, 2000). During a puissance competition, successful horses took off significantly further away from the hurdle, with take-off distance increasing with fence height (Powers, 2002). Furthermore, 'successful' horses also adopted a more vertical take-off position than unsuccessful horses (Powers, 2002).

Early studies examining jump characteristics in foals aged 6 months, found similar patterns to successful adult horses, suggesting these parameters may be useful for early selection (Santamaria *et al*., 2002). Training also impacts upon jump kinematics (Wejer *et al*., 2013), with one study finding that four months of training can significantly impact upon take-off distance, whilst further studies have indicated that jumping efficiency decreases when the number of hurdles traversed increases (Rodrigues *et al*., 2014). However, one consideration when comparing equine research to canine research is the impact of a rider upon the jump kinematics of adult horses (Lewczuk *et al*., 2006), hence research examining jump kinematics in loose schooled horses is useful. Whilst anatomically equines and canines differ it is reasonable to postulate that similarities and differences will occur when examining jump kinematics.

Research examining jump kinematics in canines, whilst still limited in comparison to equines, is beginning to expand (Birch *et al*., 2015a, b; Cullen *et al*., 2013a, b; Pfau *et al*., 2011). This could be due, in part, to participation in canine activities increasing annually, thus the need to understand the sports impact upon the health, welfare and active longevity of the dogs is paramount. Within the field of canine rehabilitation, range of motion in the joints of healthy dogs has been established, allowing for abnormal range of motion to be used as a diagnosis tool (Millis *et al*., 2004). This has also been replicated in equines (Johnston *et al*., 2004), demonstrating the need to establish the kinematics in healthy individuals before focussing on injuries.

Canine jump kinematic research to date has focused on agility dogs (Birch *et al*., 2015 a, b; Cullen *et al*., 2013a, b; Pfau *et al*., 2011; Levy *et al*., 2009). Canine agility consists of a set course primarily made up of upright hurdles, set at a predetermined height in relation to the dogs height, with the set height varying under different regulating bodies (Table I; The Kennel Club, 2013a; United Kingdom Agility, 2016). This is in stark contrast to equine show jumping and cross country whereby horses are classified by ability, not height. Competitive success in agility is largely determined by a dog's speed and accuracy and with this comes an increasing need to understand canine jump kinematics in relation to both competitive success and potential injury risk. Recently, The Kennel Club has amended their regulations with regards to jump heights, allowing all dogs to jump 10cm lower than their current measured height category from July, 2016 (The Kennel Club, 2016).

Table I

Jump height categories under Kennel Club and UK Agility regulations.

<table>
<tr><th>Height at withers</th><th>UK Agility</th><th>Kennel Club</th></tr>
<tr><td>≤ 350 mm</td><td>Mini - 300mm</td><td>Small - 350mm</td></tr>
<tr><td>351-430 mm</td><td>Midi – 400mm</td><td>Medium – 450mm</td></tr>
<tr><td>431-500 mm</td><td>Standard – 550mm</td><td rowspan="2">Large – 650mm</td></tr>
<tr><td>> 500 mm</td><td>Full – 650mm</td></tr>
</table>

Research examining injuries in agility dogs determined that hurdles, specifically landing over hurdles, tight turns upon landing and repetitive contractions of the shoulder joint, were the most common cause of injuries, with 58% of these injuries occurring during competition. Shoulders, lumbar spine and neck were the most common injury locations (Cullen *et al*., 2013a, b; Canapp, 2010; Levy *et al*., 2009). Cullen *et al*., (2013a, b) further determined previous injuries increased the risk of an agility injury whilst increasing experience decreased the risk.

When examining jump kinematics, specifically in relation to canine agility, a number of factors have been determined. Pfau *et al*., (2011) demonstrated that dogs experienced vertical forces of up to 4.5 times their body weight in their forelimbs, when jumping a hurdle compared to a long jump. Similarly, Birch and Lesniak (2012) determined an increased flexion of the shoulder and increased extension in the lumbar spine when dogs jumped a hurdle set at 51% higher than themselves compared to 7% lower than themselves. In addition, the distance between hurdles alters the kinematics of agility dogs. Dogs take-off and land closer to the hurdle and jump slower when subsequent hurdles are nearer together (Birch *et al.*, 2015a, b). Furthermore, less experienced dogs take-off and land closer to the hurdle and jump slower than more experienced dogs (Birch *et al*., 2015a). Alcock *et al*., (2015) further determined that border collies jump faster and have a larger topline angle, than non-collie breeds, with these differences being reflected in both medium and large KC height categories (Table I). Hurdle distance and experience further impacts upon apparent neck, lumbar spine and shoulder angles. These results are of particular interest due to injuries commonly occurring in these locations. Indeed, specialised rehabilitation veterinary clinics are being set up to accommodate for an increasing demand from agility competitors (Pet Rehab, 2013; The SMART clinic, 2014). Furthermore, injury risk decreases as experience increases (Cullen *et al*., 2013a), supporting the notion that significant changes in apparent joint angles may be indicative of injury. These results explain, in part, why injuries commonly occur in these locations and why injury risk may decrease as experience increases.

By determining typical jump kinematics in fit, healthy dogs, factors potentially indicative of injury could be utilised as a tool for early diagnosis (Faber *et al*., 2004; Millis *et al*., 2004). The aim of this study was to examine how certain jump kinematics altered in experienced agility dogs as hurdle height increased gradually. Length of trajectory, jumping speed (in this instance the time taken to clear the hurdle) and apparent neck, lumbar spine and shoulder angles were examined over the gradually increasing hurdle heights.

Materials and methods

The study gained ethical approval from Nottingham Trent University's School of ARES Ethical Review Group (ARES100 22/07/2014) prior to data collection. The study sample consisted of 20 border collies and border collie crosses (See table II for demographics) recruited on a voluntary basis. All of the study dogs competed and trained regularly in agility on a weekly basis and were considered fit, healthy and injury free.

Table II

Details of dogs used in the study

Breed	**Height to withers (cm)**	**Weight (kg)**	**Age (years)**	**Grade (KC Grade)[1]**
Border Collie	53	18.5	3	5
Border Collie	44	13	2	3
Border Collie	52	18	8	6
Border Collie	48	15	3	4
Border Collie	46	12	3	6
Border Collie	49	13	2	5
Border Collie Cross	58	25	6	3
Border Collie	47	13	4	5
Border Collie	49	14.5	5	6
Border Collie	52	16	2	3
Border Collie	55	20	5	7
Border Collie	53	16	4	4
Border Collie	54	16	2	4
Border Collie	53	19	4	4
Border Collie	52	18.5	6	4
Border Collie	46	14	2	4
Border Collie	50	14	6	5
Border Collie	56	21	6	3
Border Collie	52	15	2	3
Border Collie	52	19	6	7
Mean (± S.D)	51 ± 3.6	16.5 ± 3.3	4 ± 3.2	4 ± 2

Each dog was measured to the dorsal aspect of the scapula (withers), in line with current measuring techniques for agility dogs, with age, grade and weight of the dog also recorded. The study consisted of three hurdles set at 5 m apart (Birch *et al*., 2015a. b), with a high definition video camera (JVC GC-PX10 HD, 300fps) sited 5 m away from the second jump (Figure 1. Layout of the jumps used in the study. Dashed line indicates direction of travel). The second hurdle was analysed for each dog, with the field of view ensuring take-off and

[1] Kennel Club Grading System. (2016). Available at https://www.thekennelclub.org.uk/media/271056/aggradingstructure13.pdf

landing was recorded. Each dog ran the three hurdles in the same order each time, initially over a pole placed on the floor. The second repetition was set at 15 cm, with hurdle height subsequently increasing by 10 cm each repetition up to 65 cm. Each dog jumped a total of 21 hurdles during the study with this being well within normal training and competition parameters. Handlers ran their dogs as they would normally, with two dogs being withdrawn from subsequent analysis due to failing to complete one or more of the three hurdles. All dogs were tested outside on grass at their usual training venue, adding to the ecological validity of the study.

Video data were subject to downstream analysis using Dartfish software (Schmitz *et al*., 2014; Khadilkar *et al*., 2104; Eltoukhy *et al*., 2012; Borel *et al*., 2011) with the foot of the hurdle wing used to calibrate distances (52 cm). Take-off and landing distances were recorded, alongside duration of jump trajectory, allowing for jump speed to be determined. Apparent neck, lumbar spine and shoulder angles were analysed for the take-off, suspension and landing phase of the jump. Take-off distance was defined as the frame immediately prior to the dog leaving the ground and measured from the tip of the trailing hind limb to the hurdle wing (Birch *et al*., 2015a, b; Clayton, 1989). The suspension phase was determined as the midpoint of the jump in line with equine terminology (Clayton, 1989). The landing phase was determined as the first frame when the dog made contact with the ground and landing distance was measured from the back of the leading limb carpus to the hurdle wing (Birch *et al*., 2015a, b; Clayton, 1989). The jump duration was recorded between take-off and landing points. Apparent neck angle was measured from that which formed between C3, the top of the scapula and the top of the skull; lumbar spine angle was measured from that which formed between the top of the top of the ilium, base of tail and T13, whilst shoulder angle was measured from that which formed from top of humerus, the elbow and the top of scapula.

Due to agility dogs being categorised by wither height, for each dog, the percentage of the hurdle height in relation to their height at the withers was determined and used for subsequent analysis. The percentages were further categorised as 0-25%, 26-50%, 51%-75%, 76-100%, 101-125% and 126-150%. This ensured that dogs were grouped evenly (i.e. a dog of 44 cm jumping a hurdle of 55 cm would be in the same category as a dog of 53 cm jumping a hurdle of 65 cm). Results are identified as 'percentage height' throughout the results and discussion.

Kogomorov-Smirnov tests were used to asses normality followed by a principal component analysis (PCA) to asses which component was of most importance. A repeated measures analysis of variance assessed differences between percentage heights with Tukey post hoc tests used to extrapolate where these differences lay. Cohen's d effect size was calculated to examine the magnitude of the differences. Pearson's correlations were used to assess correlations and inter-observer reliability in the data with Dancy and Reidy's (2014) categorisations being used to ascribe the strength of the correlation. The alpha level was set at 0.001 with means (± standard error) used to report the differences. All statistical tests were carried out in SPSS 22.

Results

Data showed strong levels of inter-observer reliability (distances $r[56] = 0.995$, $P < 0.001$; apparent joint angles $r[117] = 0.843$, $P < 0.001$) between two independent researchers. PCA revealed height to the withers and weight (3.57 and 1.4 respectively) as the most important components in the data explaining 84% of the variability in the data. The two components showed significantly strong levels of correlation (r=0.886, P <0.05).

Jump speed and distance

As percentage height increased, there was a significant decrease in jump speed (*F*[5,134] = 42.503, *P* < 0.001; Figure 2. Mean jump speed of dogs for each percentage height. Differences lie between 0-75% and 76-150%). Tukey post hoc tests revealed dogs were significantly slower when the hurdle reached > 76% of their height to the withers. When examining length of trajectory, there was a significant difference in length of trajectory as percentage height increased (*F*[5,134] = 51.585, *P* < 0.001; Figure 3. Mean length of trajectory of dogs for each percentage height. Differences lie between 0-50%, 51-125% and 126-150%). Tukey post hoc tests revealed percentages 51-125% had a significantly longer length of trajectory compared to percentages 0-50% and 126-150%. An effect size of 0.91 and 0.94 respectively, was found, suggesting an important difference between the conditions. Furthermore, the data showed a significantly strong negative correlation between percentage height and jump speed (*r*= -0.830, *n* = 120, *P* < 0.001) and a strong positive correlation between percentage height and length of trajectory (*r* = 0.740, *n* = 120, *P* < 0.001). The results demonstrate that dogs significantly decrease in speed once the hurdle reaches > 76% of their height to the withers, whilst length of trajectory significantly increased between 51% - 125% of their height to the withers before decreasing significantly when jumping > 126% of their height to the withers.

Apparent joint angles

During the suspension phase of the jump, there was a significant flexion of the shoulder joint as percentage height increased (*F*[5,134] = 11.880, *P* < 0.001. Figure 4. Mean apparent shoulder angle during the suspension phase of the jump. Differences lie between 0-75% and 76-150%). Tukey post hoc test revealed a shoulders were significantly more flexed when the percentage height was 76-150% compared to 0-75%. An effect size of 0.94 was found, suggesting an important difference between the conditions. The data also showed a moderate negative correlation between percentage height and shoulder angle (*r*= -0.564, n = 140, *P* < 0.001). The results demonstrated that shoulder angle was significantly more flexed when dogs jumped > 76% of their height to the withers

During the landing phase of the jump, neck angles showed a significant increase in extension when percentage height increased (*F*[5,134] = 16.811, *P* < 0.001, Figure 5. Mean apparent neck angles during the landing phase of the jump. Differences lie between 0-75%, 76-125% and 126-150%). Tukey post hoc tests revealed percentages 126-150% had a significantly more acute neck angle upon landing, with 76-125% being less acute than 126-150% but more extended than 0-75%. Lumbar spine angles became significantly more extended dorsally as percentage height increased (*F*[5,134] = 6.806, *P* < 0.001, Figure 5. Mean apparent lumbar spine angles. Differences lie between 0-100% and 101-150%). Tukey post hoc tests revealed the differences to be between percentages 0-100% and 101-150%. An effect size of 0.86 and 0.85 respectively, was found, suggesting an important difference between the conditions. Furthermore, both neck and back angle showed a moderate negative correlation to percentage height (*r*= -0.589, n = 140, *P* < 0.001; *r*= -0.433, n = 140, *P* < 0.001) respectively, during the landing phase of the jump. Neck angles became more acute as percentage height increased with neck angle becoming significantly more acute when jumping > 76% of their height to the withers and then again when jumping > 126%. Lumbar spine angles became significantly more extended dorsally when jumping > 101% of their height to the withers.

Discussion

This study sought to examine how the relationship between dog height at the withers and hurdle height affected jump kinematics. The findings indicate that dogs significantly alter their jump kinematics as hurdle height increases. Previous research demonstrated a difference in kinematics over two heights of hurdles (Birch and Lesniak, 2012). This study examines these differences further by increasing jump height gradually. Theoretically, by increasing the hurdle height gradually, jump kinematics should also alter gradually. However, this was not seen with jump kinematics altering significantly when the hurdle reached 75% of their height to the withers and then again when the hurdle reached in excess of 125% of their height. These findings indicate that when a hurdle reaches these two heights specifically dogs have to significantly adapt their jump kinematics to successfully complete the hurdle. The study sample consisted of trained agility dogs, within a training environment over typical agility equipment increasing the ecological validity of the study.

PCA data revealed height to the withers and weight were the most important components as well as showing a very strong correlation. Dogs are categorised using height to the withers in agility. Consequently, this study focused on height to the withers to allow for easier end user application. Similarly, there was a strong correlation between wither height and weight (r = 0.831, n = 40, $P < 0.001$). Dogs were allocated into the categories to ensure that individual differences in height were accounted for. The smallest dog analysed was 43.5 cm at the withers whilst the tallest dog was 58 cm, thus the percentage height of the hurdle compared to their height to the withers was different. There was no effect of age or experience on the length of trajectory, jump speed or apparent joint angles as has been previously seen (Birch *et al*., 2015a, b; Cullen *et al*., 2013a, b).

Overall, jump speed decreased as hurdle height increased, whilst length of trajectory increased up to 125% before decreasing. The strong negative correlation indicates how jump speed continually decreases thus, theoretically, dogs jumping ≥ 151% of their height, as is commonly seen in working trials and gundog trials, will jump slower over these heights. However, within working trials the jump is commonly a solid object and within gundog trials they are often carrying game, therefore the jump kinematics may alter again further.

When considering length of trajectory, dogs had a significantly greater length of trajectory when the percentage height increased, with there also being a strong negative correlation between the two. Dogs jumped significantly further when jumping 51-125% of their height compared to 0-50%. However, this length of trajectory then decreased significantly when dogs were jumping ≥ 126% of their height. This is of particular interest as, unlike jump speed, length of trajectory alters significantly at this percentage height illustrating how dogs jumping ≥ 126% of their height have to significantly alter their jump kinematics to allow for hurdle clearance. This is in contrast to what is commonly seen in equines whereby take-off distance continues to increase with hurdle height (Powers, 2002). This decrease may potentially indicate that dogs are nearing their limits when clearing hurdles of this height.

This decrease in length of trajectory, coupled with apparent neck angles becoming significantly more extended upon landing demonstrates a steeper jumping bascule when dogs jump ≥ 126% of their height. Similar findings are seen in equines during a Puissance competition; however, whilst the jumping arc became steeper, the take-off distance increased as opposed to decreased (Powers, 2002). This difference could be due to the use of three consecutive hurdles in this study as opposed to one single fence as is seen in a Puissance competition. This increased extension may potentially indicate why neck injuries are commonly seen in agility dogs due to concussive forces experienced when landing over a hurdle (Cullen *et al*., 2013a, b; Pfau *et* al., 2011; Levy *et al*., 2009). Future studies could indeed examine if any correlations occur between incidences of neck injuries and height of the dog. Pfau *et al*., (2011) demonstrated that dogs experienced vertical forces of up to 4.5 times their body weight when landing over a hurdle, thus a significantly more acute neck angle could be detrimental to the health and welfare of these dogs due to the concussive forces they may experience (Zink, 2008). Interestingly, the use of Rollkur (whereby the horse's neck is forced into hyperflexion) in equines has been banned within *Fédération Équestre Internationale (FEI)* competitions on welfare grounds (von Borstel *et al*., 2009). Whilst this is flexion as opposed to extension, it illustrates the welfare implications of forced movement outside the normal range (Millis *et al*., 2004).

Apparent lumbar spine angles also differed during the landing phase of the jump, with them becoming significantly more extended dorsally when the hurdle was ≥ 101% of itself. This again is demonstrative of a steeper landing angle when percentage height increases. It could also be in order to prepare for the next hurdle. For example, a more extended neck angle could be due to the head needing to be lifted to focus on the third jump and the increased extension in the lumber spine could be aiding take off for the next hurdle (Zink, 2008). However, Birch *et al*., (2015a) demonstrated that some large dogs added a stride when hurdles were spaced at 5 m apart enabling them to decipher a more optimum take-off distance (Zink, 2008). Indeed, it is for this very reason that the hurdles in this study were spaced at 5m apart so that length of trajectory was not confounding on their take-off distances.

During the suspension phase of the jump (Clayton, 1989), shoulder angles became significantly more flexed as the percentage height increased. This supports previous kinematic studies (Birch and Lesniak, 2012) and is likely due to dogs having to tuck their forelimbs in closer to their bodies to allow hurdle clearance. Due to the lack of a clavicle, shoulder muscles are important not only for active movement but also passive movement (Budras *et al*., 2007). Thus increased, repetitive extension and flexion of the shoulder joint could explain why shoulder injuries commonly occur in agility dogs (Canapp, 2010). In contrast, the repeated extension and flexion of the shoulder joint could instead strengthen the muscles resulting in a decreased injury risk. However, strengthening of shoulder muscles is advised to be conducted in a controlled manner (Millis *et al*., 2004). Future studies examining shoulder injuries in dogs should record the height of the dog also to allow this to be examined further.

Overall, the results suggest that canine jump kinematics alter significantly at particular percentage relationships of dog height to hurdle height. This generally was between 0 - 75%, 76 - 125% and > 126%. When a hurdle reaches ≥ 76% of their height to the withers, dogs begin to significantly alter their kinematics. When the hurdle reaches ≥ 126% of their height to the withers, kinematics alter again resulting in a significantly more acute neck angle and shorter length of trajectory. The height at which a hurdle should be set at as test of athletic ability compared to the height at which a hurdle becomes a welfare concern is not yet fully understood requiring further investigation. However, due to current understanding of common injury locations and significant differences in these apparent joint angles observed when hurdle height increases, caution should be aired when categorising dogs by height to the withers. Future studies could examine heavier, short legged breeds to determine if weight, length and height had a different impact on jump kinematics. Indeed, Zink and Daniels (2011), suggest body height to weight ratios are most important when determining the height a dog should jump.

The results from this study have implications for sporting dogs required to jump, with it being the first to examine how kinematics alter over gradually increasing hurdle heights. With regards to agility specifically, for dogs measuring just into the large height category, the significant increase in neck extension for dogs falling in this category is a potential welfare concern. On the contrary, the decreased length of trajectory and jump speed could be a preventative factor in reducing injuries. However, agility is a competitive sport with this paper illustrating these dogs are unable to jump at the same speed as taller dogs, ultimately reducing the competitive nature of the sport. The recent amendments to Kennel Club jump height regulations illustrates both; the need for scientific research to be used to inform future rule changes, alongside the public support for change with regard to the health and welfare of sporting dogs.

Conclusion

This study illustrates how canines alter their jump kinematics as percentage height increases. As percentage height increases, jump speed decreases whilst length of trajectory increases. The study indicates that once a dog reaches a hurdle $\geq$ 76% of their height, their kinematics alter, with this then altering further when the hurdle reached $\geq$ 126% of their height. This study adds to our current understanding of canine jump kinematics and should be used to inform training plans for agility dogs particularly when dogs are jumping in excess of 126% of their height to the withers.

Conflict of interest

J. Boyd is a member of The Kennel Club's Activities Health and Welfare Subgroup. None of the other authors of this paper has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of the paper.

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References

Alcock, J., Birch. E., Boyd, J., 2015. Effect of jumping style on the performance of large and medium elite agility dogs. Journal of Comparative Exercise Physiology 11(3), 145-150.

Birch, E., Boyd, J., Doyle, G., Pullen. A., 2015a. The effects of altered distances between hurdles on the jump kinematics and apparent joint angulations of large agility dogs. The Veterinary Journal 204, 174-178.

Birch, E., Boyd, J., Doyle, G., Pullen. A., 2015b. Small and medium agility dogs alter their kinematics when the distance between hurdles differs. Comparative Exercise Physiology 11(2), 75-78.

Birch, E., Lesniak, K., 2012. Effect of fence height on joint angles of agility dogs. The Veterinary Journal 198: e99-e102.

Borel, S., Schneider, P., and Newman, C. J., 2011. Video analysis software increases the interrater reliability of video gait assessments in children with cerebral palsy. Gait and Posture 33, 727-729

Budras, K. D., McCarthy, P. H., Frike, W., Richter, R. (Eds), 2007. In: Anatomy of the Dog. Fifth Edn. Schlütersche Verlagsgesellschaft, Hannover, Germany, pp. 16-27.

Canapp, S., 2007. Shoulder conditions in agility dogs. Focus on Canine Sports Medicine. http://www.akcchf.org/assets/files/canine-athlete/Biceps-injury.pdf. (accessed 17 June 2015)

Clayton, H. M., 1989. Terminology for the description of equine jumping kinematics. Journal of Equine Veterinary Science 9, 341-348.

Clayton, H. M., Barlow, D. A., 1989. The effect of fence height and width on the limb placements of show jumping horses. Journal of Equine Veterinary Science 9, 179-185.

Colborne, G., R., 2007. Bringing canine biomechanics out of the dark ages. The Veterinary Journal 173, 469-470.

Cullen, K. A., Dickey, J. P., Bent, L. R., Thomason, J. J., Moens, N. M. M., 2013a. Internet-based survey of the nature and perceived causes of injury to dogs participating in agility training and competition events. Journal of the American Veterinary Medical Association 243, 1010-1018.

Cullen, K. A., Dickey, J. P., Bent, L. R., Thomason, J. J., Moens, N. M. M., 2013b. Survey-based analysis of risk factors for injury among dogs participating in agility training and competition events. Journal of the American Veterinary Medical Association 243, 101-1024.

Dancy, C., Reidy, J., 2014. Statistics without maths for Psychology. 6th Edition. Pearson Education Limited: Essex.

Eltoukhy, M., Asfour, S., Thompson, C., and Latta, L., 2012. Evaluation of the Performance of Digital Video Analysis of Human Motion: Dartfish Tracking System. International Journal of Scientific and Engineering Research 3(3), 1-6.

Faber, M., Johnston, C., van Weeren, P. R., and Barneveld, A., 2002. Repeatability of back kinematics in horses during treadmill locomotion. Equine Veterinary Journal 34(3), 235-241.

Gilette, R., Angle, T., 2008. Recent developments in canine locomotor analysis: A review. The veterinary Journal 178, 165-176.

Hole, S. L., Clayton, H. M., Lanovaz, J. L., 2002. A note on the linear and temporal stride kinematics of Olympic show jumping horses between two fences. Applied Animal Behaviour Science 75, 317-323.

Khadilkar, L., MacDermid, J. C., Sinden, K. E., Jenkyn, T. R., Birmingham, T. B., and Athwal, G. S., 2014. An analysis of functional shoulder movements during task performance using Dartfish movement analysis software. International Journal of Shoulder Surgery 8(1), 1-9.

Levy, M., Hall, C., Trentacosta, N., Percival, M., 2009. A preliminary retrospective survey of injuries occurring in dogs participating in canine agility. Veterinary and Comparative Orthopaedics and Traumatology 22, 321-324.

Lewczuk, D., Sloniewski, K., Reklewski, Z., 2006. Repeatability of the horse's jumping parameters with and without the rider. Livestock Science 99, 125-130.

Millis, D. L., Levine, D., Taylor, R. A., 2004. Canine Rehabilitation and Physical Therapy. Saunders, USA.

Pet Rehab, 2013. Pet rehab fitness training. http://pet-rehab.co.uk/fitness-training/ (accessed 17 June 2015)

Pfau, T., Garland de Rivaz, A., Brighton, S., Weller, R., 2011. Kinetics of jump landing in agility dogs. The Veterinary Journal 190, 278-283.

Powers, P., 2002. The take off kinematics of jumping horses in a *puissance* competition. 20th International Symposium on Biomechanics in Sport, Extremadure, Spain, 1-5 July 2002, https://ojs.ub.uni-konstanz.de/cpa/article/view/667/589 (accessed 3 February 2015).

Powers, P. N. R., Harrison, A. J., 2000. A study on the techniques used by untrained horses during loose jumping. Journal of Equine Veterinary Science 20, 845-850.

Powers, P. N. R., Harrison, A. J., 1999. Models for biomechanical analysis of jumping horses. Journal of Equine Veterinary Science 19, 799-806.

Rodrigues, T. N., Godoi, F. N., Ramos, M. T., Andrede, A. M., Almeida, F. Q., 2014. Changes in kinematics during repeated jumping. Equine Veterinary Journal 46, 47-48.

Santamaria, S., Back, W., van Weeren, P. R., Knaap, J., Barneveld, A., 2002. Jumping characteristics of naïve foals: lead changes and description of temporal and linear parameters. Equine Veterinary Journal 34, 302-307.

Schmitz, A., Ye, M., Shapiro, R., Yang, R., and Noehren, B., 2014. Accuracy and repeatability of joint angles measured using a single camera markerless motion caption system. Journal of Biomechanics 47, 587-591.

Smart Clinic, 2014. Welcome to SMART vet Wales. http://www.smartvetwales.co.uk./ (accessed 17 June 2015)

The Kennel Club, 2013. Agility. http://www.thekennelclub.org.uk/activities/agility/ (accessed 17 June 2015)

The Kennel Club, 2013. Activities. http://www.thekennelclub.org.uk/activities/ (accessed 17 June 2015)

The Kennel Club, 2016. Lower jump height option in agility introduced by the kennel club. http://www.thekennelclub.org.uk/media/743020/press_release_2016_agility_the_kennel_club_announce_the_introduction_lower_height_option_jumps_v8.pdf (accessed 01/02/2016)

United Kingdom Agility, 2016. Rules and Regulations 2016. http://www.ukagility.com/Downloads/UKARules2016.pdf (accessed 01/02/2016)

Vogel, C., 1996. The Complete Performance Horse. David and Charlis Lts, Ohio

Von Borstel, U. U., Duncan, H, J, I., Shoveller, A. K., Merkies, K., Keeling, L. J., Millman, S. T., 2009. Impact of riding in a coercively obtained Rollkur posture on welfare and fear of performance horses. Applied Animal Behaviour Science 116(2-4), 228-236.

Wejer, J., Lendo, I., Lewczuk, D., 2013. The effect of training on the jumping parameters of inexperienced Warmblood horses in free jumping. Journal of Equine Veterinary Science 33, 483-486.

Zink, C. 2008. The agility advantage; Health and Fitness for the Canine Athlete) Clean Run Publishing; USA.

Zink, C., Daniels, J., 2011. Jumping from A to Z: Teach your dog to soar. Dogwise Publishing; Wenatchee, WA.