The Influence of Harness Design on Forelimb Biomechanics in Pet Dogs

Lauren Dowdeswell and Lucianna Churchill, University Centre Reaseheath

Abstract

Dog harnesses are a popular walking aid for pet dogs. Research has focused on the biomechanical impact of assistance dog harnesses; however, this is lacking in the pet dog harness industry. This study aimed to explore the impact of six different harness types on canine biomechanics compared to a standard (base) collar, specifically analysing shoulder extension, shoulder flexion, elbow extension and elbow flexion. A high-speed recording device recorded a total of 21 videos per dog (n=30), and analysis demonstrated that the straight-front harness allowed for the most elbow and shoulder extension and flexion, whereas the front clip allowed for the least elbow and shoulder flexion and extension. By directly comparing the six harnesses, three of which are new to research inclusion, the evidence drawn demonstrates which harnesses should be utilised more and which should potentially be avoided. These results provide a foundation for future research, and recommendations have been outlined, specifically considering breed difference, morphological impacts and long-term effects of harness design on canine gait. With advancements in the canine industry, this research is crucial for maximising safety and potentially preventing or delaying various musculoskeletal disorders.

Keywords: Biomechanical impact of pet dog harnesses, Elbow and Shoulder flexion and extension, Canine gait during harness use, Canine pet harnesses, Quintic Software for canine gait analysis, Restrictive vs. non-restrictive harnesses

Introduction

The use of harnesses for pet, working and sport dogs is becoming increasingly popular in the United Kingdom (Cobb *et al.*, 2015; Grainger *et al.*, 2016; Shih *et al.*, 2021). Research has explored the use of harnesses on guide dogs (Peham *et al.*, 2013), and the behavioural impacts of harnesses (Grainger *et al.*, 2016; Kumpulainen *et al.*, 2021); however, there is a noticeable lack of research focusing on harnesses for pet dogs. Harness brands Ruffwear (2020) and Julius K9 (2020b) have conducted research to demonstrate the benefits of their own harnesses, however there are no comparisons between brands. There is a risk that research conducted by parties with financial investment may withhold data to maintain a positive public image (Fabbri *et al.*, 2018), which therefore lowers the reliability of their findings.

Canine biomechanics

Nagymáté *et al.* (2018) conducted gait analysis using three Julius K9 harnesses and found no significant differences between the three harnesses when compared to unleashed movements. This directly challenges Julius K9's reputation for causing shoulder injuries and limiting movement (Thompson, 2020). Julius K9 (2020a) states that this opinion is caused by a lack of research and misinformation spread on social media.

Pálya *et al.* (2022) completed a follow-up study investigating two 'restrictive' harnesses and two 'non-restrictive' harnesses, including three Julius K9-branded harnesses. They could not recommend one particular harness, as the results gathered depended on the breed and use of the harness (Edmunds *et al.*, 2021). This further shows that harness impact depends mainly on the build of the individual dog, suggesting that opinions on certain brands should not be generalised.

Zink (2019) hypothesised that a straight-front harness would restrict movement more than a y-front harness, but found the opposite. They assessed gait at walking speed and trot speed, and found that the y-front allowed for less shoulder extension than the straight front. They assumed this to be caused by incorrect harness fitting and is therefore a limitation of the study as other research has shown that ill-fitting harnesses can impact gait (McMillan and Spaulding, 2022).

Lafuente *et al.* (2018) completed a similar study utilising a treadmill but implemented markers on the dogs for angle analysis. They also found y-shaped harnesses reduced shoulder extension more than the straight front. While markers can increase accuracy (Moro *et al.*, 2022), studies have shown that markers can influence the dogs' natural motion due to the treadmill pressure increasing skin movement (Schwencke *et al.*, 2012). This means that markers may lead to inaccurate results due to the causation of extraneous variables.

Söhnel *et al.* (2022) advocate for treadmill-based gait analysis due to its speed consistence and reduced movement variability compared to overground locomotion. However, Piccione *et al.* (2012) expressed that minimal treadmill experience may impact a dogs' behaviour, therefore influencing their gait. Treadmills only allow for the joints to perform certain movements (Torres *et al.*, 2013), which could potentially alter their gait (McIntyre, 2019). This may misrepresent the impact of harnesses on typical pet usage.

Musculoskeletal disorders

O'Neill *et al.* (2017) identified that musculoskeletal disorders, such as osteoarthritis, are a leading cause of death in German Shepherd Dogs. Mocchi *et al.* (2020) found extensive reports of osteoarthritis in veterinary practices. Osteoarthritis is the irreversible, progressive degeneration of bone and cartilage (Zeira *et al.*, 2018). Belshaw *et al.* (2020) looked into gait changes caused by osteoarthritis, finding that exercise was severely impacted. Considering the influence of a harness on the musculoskeletal system, it is likely that dogs will adapt their gait to accommodate a harness during exercise, and this adaptation may be more severe if the harness is ill-fitting (Anderson, 2020).

Harnesses can alter posture, causing asymmetries between specific joints (Packer and Tivers, 2015). This can significantly impact breeds with conformational disorders, such as English Bulldogs (Escobar *et al.*, 2017). Conformational disorders occur in breeds with exaggerated body structures, causing negative impacts to their health and welfare (Packer *et al.*, 2023). These body structures have been shown to influence the movement of different limbs and joints due to the predisposition of orthopaedic diseases and the interference with locomotion, causing changes in asymmetry and peak vertical force (Escobar *et al.*, 2017; Humphries *et al.*, 2020a; Humphries *et al.*, 2020b; Jeandel and Garosi, 2018).

Injury can lead to gait abnormalities due to compensating to reduce weight-bearing on the affected limb(s) (Carapeba *et al.*, 2016; Goldner *et al.*, 2018). Żuk and Księżopolska-Orłowska (2015) investigated arthritis in children, finding a reduced range of motion in the affected limb, and microtrauma in the unaffected limb. Although this research investigated children, Meeson *et al.* (2019) recently discovered that both dogs and humans share commonalities in osteoarthritis, such as areas of development, and causes of development. Due to this, it is likely that dogs would show similar gait abnormalities caused by the compensation.

Additionally, equine research has established that lameness causes compensatory weight redistribution onto the non-affected limbs, resulting in gait abnormalities due to the transfer of vertical force (Bragança *et al.*, 2020; Clayton, 2016; Maliye and Marshall, 2016). Given the musculoskeletal similarities between horses and dogs, similar compensatory redistribution is expected in dogs (Ahmed *et al.*, 2019).

Alternatives to harnesses

Many trainers and behaviourists recommend the use of collars over harnesses due to the misconception that harnesses actively cause a dog to pull (Landsberg *et al.*, 2023). This is incorrect; harnesses were designed to enable sled dogs to pull (Ramey *et al.*, 2022), but they do not inherently cause pulling (Shih *et al.*, 2020).

Townsend *et al.* (2020) stated that collars can cause tracheal and oesophageal issues, especially in brachycephalic breeds. Harnesses can prevent this by redistributing pressure across the body (Carter *et al.*, 2020; Hunter *et al.*, 2019). However, Shih *et al.* (2021) found this enabled significantly more pulling, so headcollars may be more suitable for these dogs (Grainger *et al.*, 2016). The AKC (2021) express that harnesses help to avoid injury and discourage pulling but have a greater escape risk. Both Takáčová *et al.* (2021) and Ward (2021) state that this is usually due to user fitting error, rather than harness design, so still recommends their use.

Gaps in the research

Despite the vast array of harness designs available, comparative biomechanical research is severely limited. Blake *et al.* (2019) emphasised the need for direct comparisons between multiple harness designs, specifically in relation to gait. Improved understanding of the biomechanical impacts of harnesses may aid in harness production, ensuring brands offer safe and secure harnesses. Furthermore, statistical information on a wider variety of harnesses is needed so owners can make informed decisions by providing results on the impact each style/design can have on biomechanics.

This study will close this gap by investigating the influence of harness design on shoulder and elbow biomechanics, specifically flexion and extension, in pet dogs. This new approach may facilitate the further study of the long-term effects of harnesses. This research will provide the vital information needed for owners to choose harnesses and to bring awareness to the variety of styles available.

Canines have various morphologies depending on their breed (Bannasch *et al.*, 2021). Improving owner awareness of the variety of harnesses available means they are more adept to finding a well-fitting, suitable harness. This can therefore prevent the risk of harnesses having a negative impact on the dogs' biomechanics (Preston *et al.*, 2012).

Methodology

Data collection occurred at the University Centre Reaseheath (UCR), utilising various indoor classrooms to avoid weather-related disruptions (Edwards *et al.*, 2018). Advertisement of the study was released on social media in an attempt to achieve the desired sample size (n=30). This surpasses similar research, and provided sufficient data within the time constraints (Morse, 2015). Ethical approval was obtained on 25 June 2022, before data collection began, from the UCR Ethics Committee, in accordance with the Animal Welfare Act 2006 (ethics approval reference 221405LDsub4).

The study was open to all dogs, excluding the four banned breeds in the UK (Pitbull Terrier, Japanese Tosa, Dogo Argentino and Fila Brasileiro; The Dangerous Dogs Act, 1991). Due to accepting all breeds, one harness of each size, per harness type, was required. Dogs had to be over the age of 18 months to prevent the open growth plates of puppies causing abnormal results (Virag *et al.*, 2022). They also had to be fit and well, with no existing musculoskeletal disorders, due to these impacting biomechanics (Adrian *et al.*, 2019) or causing harm/discomfort (Shih *et al.*, 2021).

Participants were recruited through social media advertisement explaining the study and inviting participation. Staff who enrolled their dogs in the university kennels were also approached regarding the inclusion of their dogs. These were included due to the convenient access to the dogs during the working day.

Potential participants were required to complete a pre-trial questionnaire per dog before their trial could begin. Three screening questions were included to ensure three main requirements. The first being that the owner was at least 18 years old (UK General Data Protection Regulation, 2021). Secondly, that the dog was over 18 months old. Finally, ensuring the dog had no known musculoskeletal disorders.

The remainder of the questionnaire gathered information pertaining to each participant, such as breed and age. All owners were asked if their dog was likely to become distressed during harness fitting. If yes, the participant was excluded to ensure researcher safety (Thompkins *et al.*, 2016).

Video data were collected using a high-speed 60fps (frames per second) camera (iPhone 11), for simplicity and availability. Each dog was fitted with a collar as a control measure (Simmons *et al.*, 2015), and each harness was fitted by, or under the guidance of, the author. This was to ensure they were correctly fitted and sized to avoid either factor becoming an extraneous variable and influencing results (Bremhorst *et al.*, 2018).

Each dog was walked down a 4m (metre) walkway on a 1.3m lead, marked using a 5m lead, with a camera situated 1–2m away on a stand. This distance was altered depending on the height of the dog. Three repetitions per harness/collar were recorded; any unsuccessful videos were re-recorded. Each video was then transferred onto the study laptop via Telegram and saved in a password-protected Microsoft Vault.

While all participants were trialled in the same harnesses, the order of these was randomised. This may have negated the impacts of habituation to harness wear or trial behaviour expectations (Suresh, 2011). This is especially relevant for dogs who do not normally wear harnesses. Future research should consider the benefits of randomised studies and/or training prior to the trial.

The independent (explanatory) variable was the harness style (see Appendix 1), and the dependent (response) variable were elbow extension, elbow flexion, shoulder extension and shoulder flexion (see Appendices 2 and 3). This study included a third variable, a (random) data variable, which was the dogs involved. As a control measure, each dog was walked on the base collar to establish an approximate base-gait measurement. Owners picked the direction of walking, and this remained constant for each video to ensure directional changes had no impact.

Videos were then analysed using Quintic Biomechanics Software (Quintic Software, 2009), due to its ability to provide high-speed video capture and its allowance for biomechanical analysis. For each video, the gait cycle was broken into three phases: (1) full elbow extension/shoulder flexion (as we can measure the different angles on the same frame), (2) elbow flexion and (3) shoulder extension (see Appendices 2 and 3). These were then measured using Quintic Manual Angular Software.

Each angle was then exported onto a large Excel document for each walk. The mean and R Studio were used to fully analyse the data. Primary data was collected; although this can be more expensive and time-consuming to complete, data gathered first-hand has increased reliability and validity (Vetter, 2017).

A Generalised Linear Mixed Model (GLMM) was used for data analysis, due to being appropriate for large amounts of clustered data (Rabe-Hesketh and Skrondal, 2010); this study collected approximately 2500 individual pieces of data. As previously noted, three different walks were recorded per dog per harness per angle. From there, each individual piece of data was put onto a final data set, before being uploaded onto R Studio for GLMM analysis. Outliers have not been removed, as GLMMs are flexible and can handle random effect and non-normal distributions, so this step was not necessary (Bolker *et al.,* 2009). Alongside this, the median and interquartile range were found for each harness type and angle (as shown in Table 1).

Due to the third, random variable – the dogs themselves – the GLMM accounted for this by basing itself on the entire sample population instead of each individual subject, which allowed for sparse sampling (Huang and Li, 2007). This is why the raw data set was used, as GLMM works best with large sets of data instead of means, and it can appropriately incorporate/exclude any outliers.

A normality test is not required for a GLMM due to the large amount of data it handles and the assumption that there will be non-normal results within the data collected (Stroup, 2015). However, an omnibus normality test (Shapiro-Wilk) was still performed to assess the normality of the whole data set ($p=0.05$) and to justify the correct descriptive statistics to report. The data was not normally distributed ($p<0.05$), so the median and interquartile range were used to remain consistent across the data.

Alongside this, 28 individual Shapiro-Wilkes normality tests were performed for each harness/collar and angle combination (elbow extension/straight front, elbow extension/chest plate, for example – see Appendix 4) as supplementary information. Although some of these normality tests were normal, if there is any non-normal data then the assumption that the entire dataset is non-normal is made (Field, 2017).

However, these normality tests were used to decide which pairwise tests to use for the result comparisons. A one-way ANOVA was used for shoulder flexion as all results were normal, and a Kruskal Wallis was used for the other three angles, as the results were a mixture of normal and non-normal.

Health and safety, and ethics

The health and safety, and ethics for this study were upheld, meaning this research was ethically produced, and demonstrates to future researchers how to ethically conduct dog-related studies (Woodin, 2015). Particularly, one dog was excluded from the trial due to their negative reaction to the study location, so removing him from the study was the most ethical decision (Tasker *et al.*, 2018).

Alongside this, participants never came into contact with other dogs outside of their household (King and Zohny, 2022). Timeslots were given to each participant, allowing sufficient time for them to leave before the next participant's trial. This ensured that dogs did not come into contact with each other; to give us time to finish each harness; and to ensure the dog had time to acclimatise to the room before beginning the trial.

Any dogs with nervousness or disfavour of having their paws touched were handled by the owner to protect researchers from any reactions (Health and Safety at Work Act 1974), but to also keep anxiety levels of the dogs as low as possible (Animal Welfare Act 2006). Although changing the walker for some dogs may be an extraneous variable, the author prioritised the ethics and safety of each participant as paramount (National Dog Warden Association, 2012).

Results

A GLMM was performed to compare the influence of each harness on elbow and shoulder extension and flexion. Descriptive statistics are presented in Table 1, with results expressed as medium and interquartile range.

Results are recorded as (median (IQR: 25th percentile – 75th percentile)).

Joint	Angle	Base Collar		Chest Plate		Front Clip		No-Pull		Step-In		Straight Front		Y-Front	
		Med	*IQR*	*Med*	*IQR*	*Med*	*IQR*	*Med*	*IQR*	*Med*	*IQR*	*Med*	*IQR*	*Med*	*IQR*
Shoulder	Extension	97.4°	88.5° - 102.5°	88.5°	80.9° - 97.6°	84.7°	79.6° - 95.2°	88.2°	76.8° - 95.2°	86.3°	80.9° - 96.2°	93.8°	86.0° - 99.6°	93.5°	84.3° - 99.3°
	Flexion	91.3°	85.9° - 97.6°	88.4°	82.5° - 94.5°	84.1°	78.2° - 90.7°	85.7°	79.7° - 91.2°	87.6°	82.8° - 93.8°	89.6°	85.4° - 94.9°	88.9°	84.4° - 93.8°
Elbow	Extension	137.0°	131.8° - 141.4°	134.2°	130.5° - 138.3°	132.1°	127.1° - 135.2°	133.2°	128.3° - 136.7°	133.9°	129.4° - 139.3°	134.6°	130.1° - 140.4°	135.9°	130.8° - 139.7°
	Flexion	80.9°	73.7° - 86.9°	81.4°	74.0° - 84.2 °	76.4°	69.6° - 81.0°	78.0°	74.0° - 83.1°	75.7°	71.0° - 80.5°	79.7°	75.9° - 84.3°	79.5°	75.2° - 85.0°

Table 1: Median and interquartile range of each harness design and base collar

The influence of each harness design on shoulder and elbow extension and flexion, compared to the base collar is displayed. The descriptive statistics are recorded as (median (IQR 25th percentile – 75th percentile)).

As indicated below in Figure 1, the front clip (132.1° (IQR: 127.1° – 135.2°)) and no-pull (133.2° (IQR: 128.3° – 136.7°)) had the most significant impact on elbow extension compared to the base collar (137.0° (IQR: 131.8° – 141.4°)). The chest plate (134.2° (IQR: 130.5° – 138.3°)) and step-in (133.9° (IQR: 129.4° – 139.3°)) both had a significant impact, but less so than the aforementioned harnesses. However, neither the straight front (134.6° (IQR: 130.1° – 140.4°)) or y-front (135.9° (IQR: 130.8° – 139.7°)) had a significant impact on elbow extension.

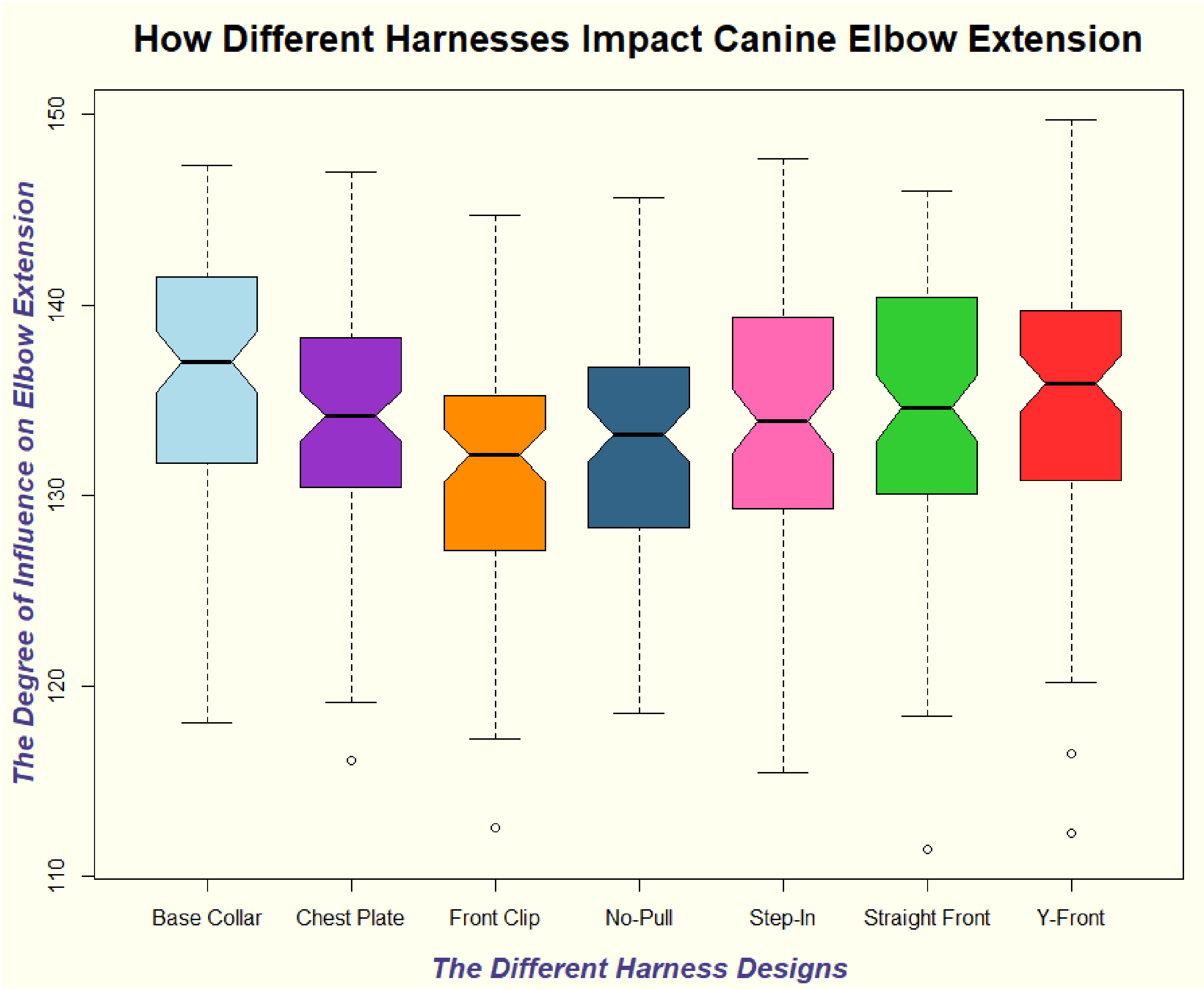

Figure 1: Box-and-whisker plot showing elbow extension for each harness design

The degree of canine elbow extension for each harness design and base collar is displayed (n=60). This is displayed as a box-and-whisker plot with outliers.

(GLMM: chest plate t = -0.942, p=0.034; front clip t = -2.123, p<0.001; no-pull t = -5.642, p<0.001; step-in t = -4.057, p=0.027; straight front t = -2.210, p=0.078; y-front t = -1.765, p=0.346).

Conveyed in Figure 2, the front clip (76.4° (IQR: 69.6° – 81.0°)) and step-in (75.7° (IQR: 71.0° – 80.5°)) had the most significant impact on elbow flexion compared to the base collar (80.9° (IQR: 73.7° – 86.9°)). The no-pull (78.0° (IQR: 74.0° – 83.1°)) also had a significant impact, but not to a considerable degree. The straight front (79.7° (IQR: 75.9° – 84.3°)), y-front (79.5° (IQR: 75.2° – 85.0°)) and chest plate (81.4° (IQR: 74.0° – 84.2 °)) did not have a significant impact on elbow flexion. (See Appendix 5 for the pairwise comparisons).

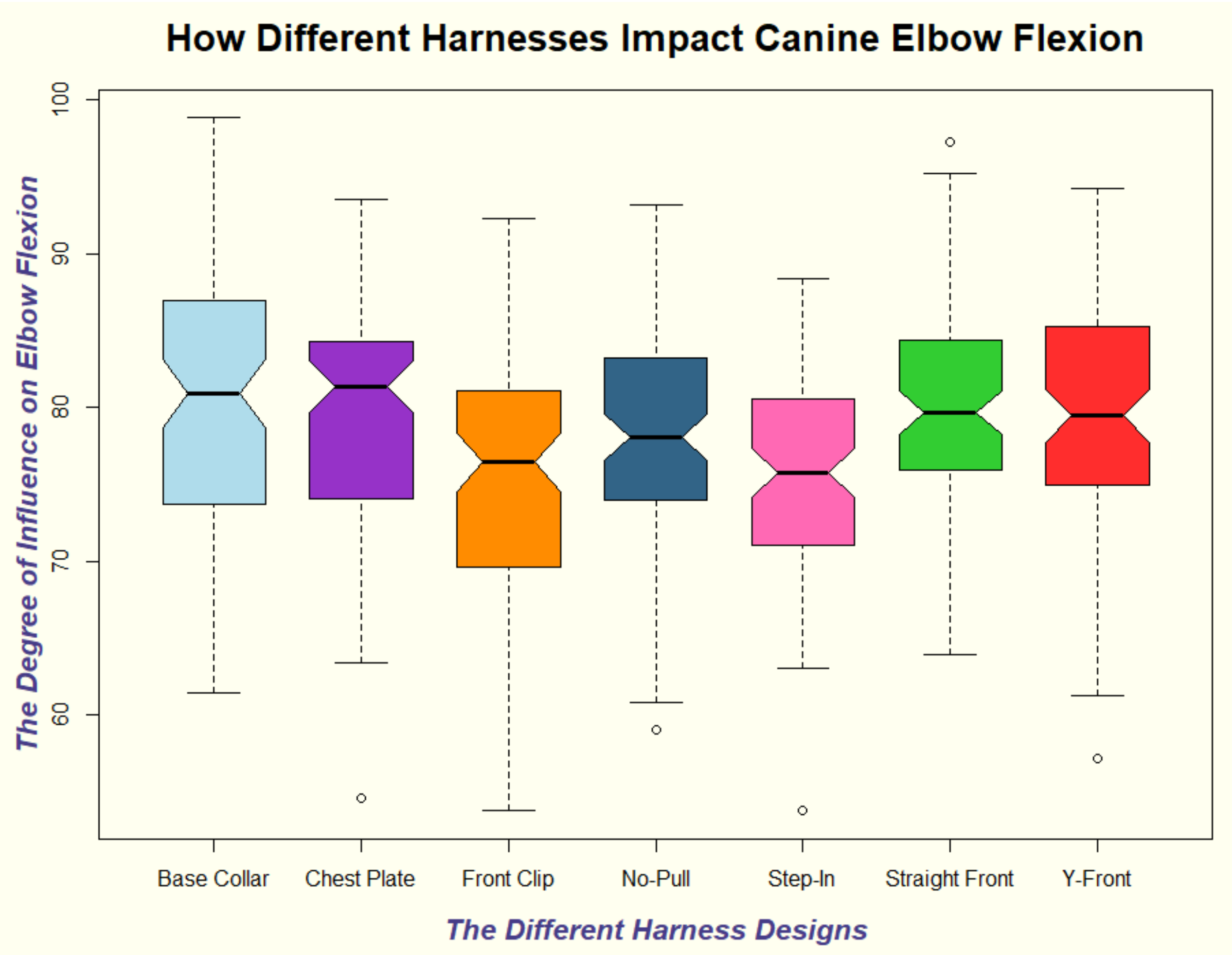

Figure 2: Box-and-whisker plot showing elbow flexion for each harness design

The degree of canine elbow flexion for each harness design and base collar is displayed (n=60). This is displayed as a box-and-whisker plot with outliers.

(GLMM: chest plate t = -0.755, p=0.511; front clip t = -0.658, p<0.001; no-pull t = -5.769, p=0.003; step-in t = -3.006, p<0.001; straight front t = -5.471, p=0.501; y-front t = -0.673, p=0.451).

Exhibited in Figure 3, the chest plate (88.5° (IQR: 80.9° – 97.6°)), front clip (84.7° (IQR: 79.6° – 95.2°)), no-pull (88.2° (IQR: 76.8° – 95.2°)), step-in (86.3° (IQR: 80.9° – 96.2°)), straight front (93.8° (IQR: 86.0° – 99.6°)) and y-front (93.5° (IQR: 84.3° - 99.3°)) all had a significant impact on shoulder extension compared to the base collar (97.4° (IQR: 88.5° – 102.5°)). (See Appendix 6 for the pairwise comparisons).

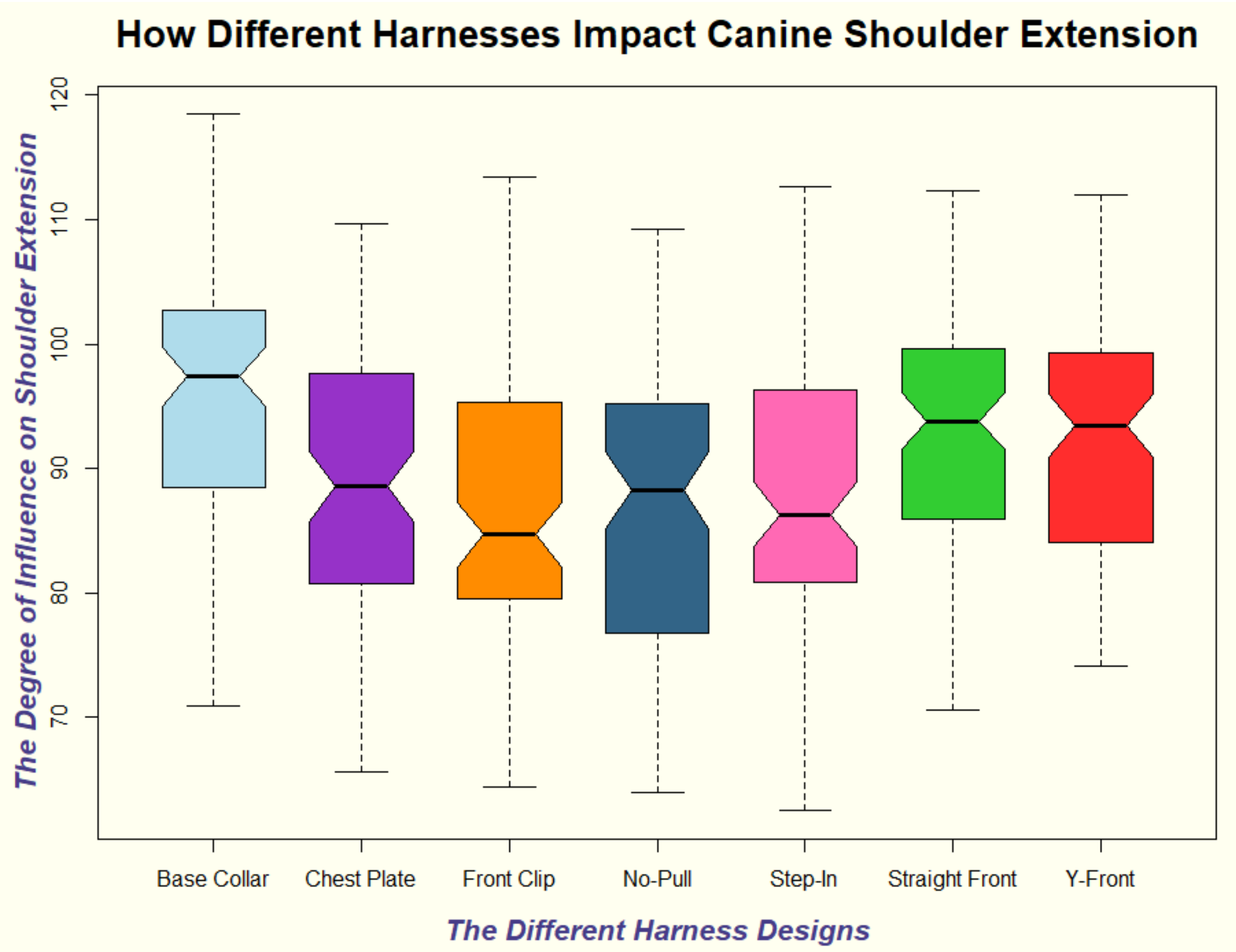

Figure 3: Box-and-whisker plot showing shoulder extension for each harness design

The degree of canine shoulder extension for each harness design and base collar is displayed (n=60). This is displayed as a box-and-whisker plot with outliers.

(GLMM: chest plate t = -3.863, p<0.001; front clip t = -7.403, p<0.001; no-pull t = -9.514, p<0.001; step-in t = -10.030, p<0.001; straight front t = -8.340, p<0.001; y-front t = -3.547, p<0.001).

Displayed in Figure 4, the chest plate (88.4° (IQR: 82.5° – 94.5°)), front clip (84.1° (IQR: 78.2° – 90.7°)), no-pull (85.7° (IQR: 79.7° – 91.2°)), step-in (87.6° (IQR: 82.8° – 93.8°)) and y-front (88.9° (IQR: 84.4° – 93.8°)) all had a significant impact compared to the base collar (91.3° (IQR: 85.9° – 97.6°)). The only harness to not significantly impact shoulder flexion was the straight front (89.6° (IQR: 85.4° – 94.9°)). (See Appendix 7 for the pairwise comparisons).

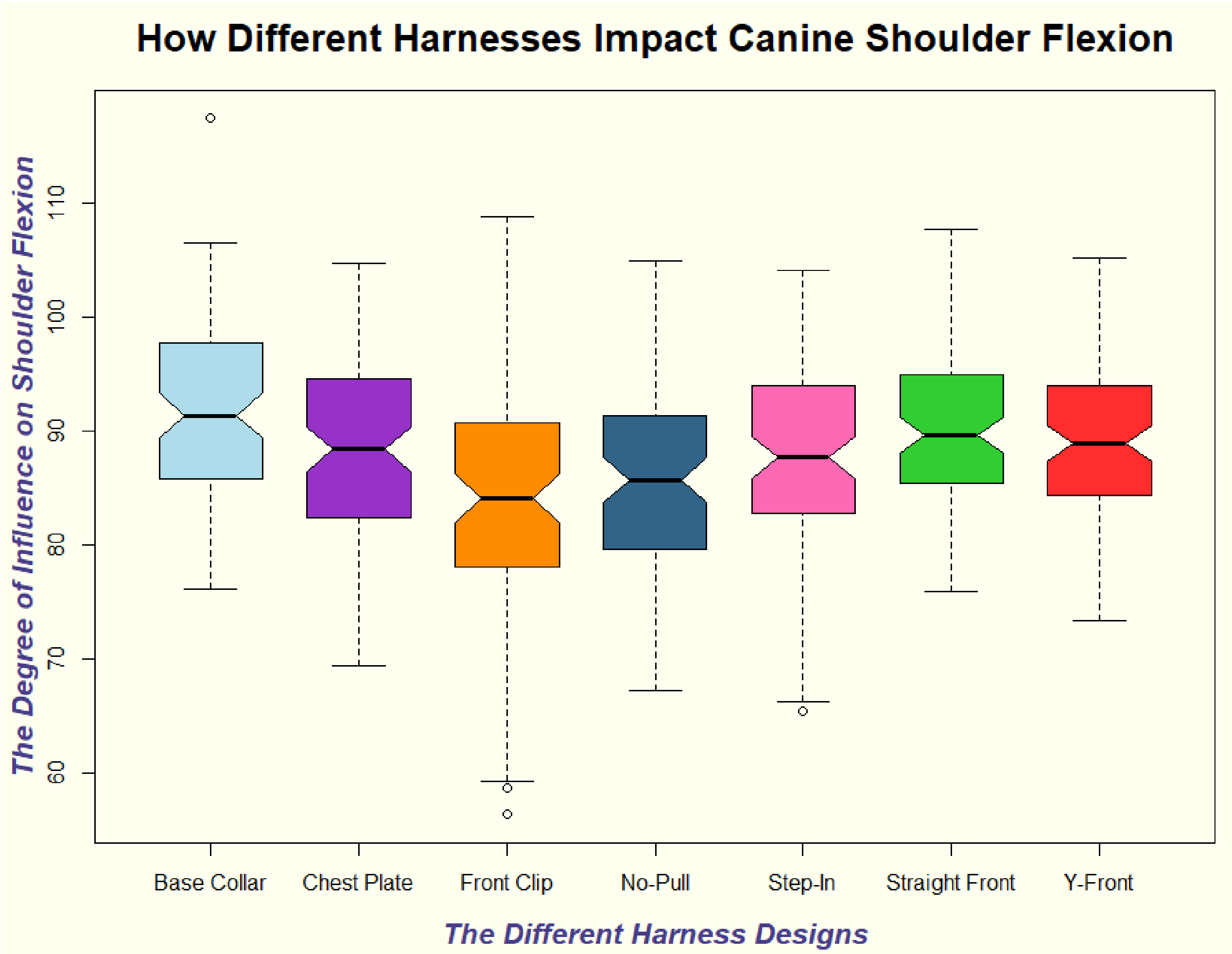

Figure 4: Box-and-whisker plot showing shoulder flexion for each harness design

The degree of canine shoulder flexion for each harness design and base collar is displayed (n=60). This is displayed as a box-and-whisker plot with outliers.

(GLMM: chest plate t = -3.557, p<0.001; front clip t = -4.736, p<0.001; no-pull t = -9.184, p<0.001; step-in t = -7.824, p<0.001; straight front t = -5.079, p=0.02; y-front t = -2.330, p<0.001).

Across all four analyses, the front clip is the only harness that significantly reduced all four angles measured. Opposingly, the straight-front harness did not significantly reduce three of the angles measured. The only significant reduction was of shoulder extension; however, every harness significantly reduced this angle compared to the collar. The y-front did not significantly reduce elbow extension or flexion but did significantly reduce shoulder extension and flexion. (See Appendix 8 for the ANOVA and Tukey honest significant difference post-hoc).

The chest plate did not reduce elbow flexion, but significantly reduced both shoulder extension and flexion. It also reduced elbow extension, but to a lower statistical degree. Finally, the no-pull and step-in both reduced every angle, with both significantly reducing shoulder extension and flexion. Both harnesses reduced elbow flexion, but the reduction was more significant in the step-in. Similarly, both also reduced elbow extension, but the reduction was more significant in the no-pull.

Alongside reporting the median and interquartile range, the mean and standard deviation (mean +/- standard deviation) were noted, as presented in Table 2 below. This table displays the influence of each harness design on shoulder and elbow extension and flexion. The coloured shadings are explained in Figure 5. Furthermore, a post-hoc test was performed for each angle to show more clearly where the differences lie between each harness/collar, and which are significant.

Joint	Angle	Lorke et al., 2017 Maximum Angles	Base Collar	Chest Plate	Front Clip	No-Pull	Step-In	Straight Front	Y-Front
Shoulder	Extension	138.3° +/- 7.2°	95.7° +/- 9.7°	89.0° +/- 10.7°	87.1° +/- 11.3°	86.6° +/- 11.2°	88.1° +/- 10.1°	92.3° +/- 8.9°	92.1° +/- 10.1°
	Flexion	104.5° +/- 6.1°	91.9° +/- 7.6°	87.9° +/- 8.0°	84.3° +/- 10.3°	85.3° +/- 8.0°	87.6° +/- 8.0°	89.8° +/- 7.0°	88.8° +/- 7.7°
Elbow	Extension	152.0° +/- 10.5°	135.8° +/- 7.2°	134.1° +/- 5.8°	131.2° +/- 6.7°	132.5° +/- 6.0°	134.0° +/- 6.4°	134.4° +/- 7.1°	135.0° +/- 6.7°
	Flexion	83.2° +/- 11.1°	80.4° +/- 8.9°	79.8° +/- 7.4°	75.4° +/- 6.7°	77.7° +/- 7.0°	75.6° +/- 6.1°	79.7° +/- 6.5°	79.7° +/- 6.9°

Table 2: Mean and standard deviation of each harness design and base collar

The influence of each harness design on shoulder and elbow extension and flexion, compared to the base collar is displayed. The descriptive statistics are recorded as (mean +/- standard deviation).

Highlighting Key

Least Impact on Gait

- harness which allows the most extension/flexion
- harness which allows the second most extension/flexion
- harness which allows the third most extension/flexion
- harness which allows the third least extension/flexion
- harness which allows the second least extension/flexion
- harness which allows the least extension/flexion

Most Impact on Gait

Figure 5: The highlighting key for Table 2

This key displays the harnesses in order of most extension/flexion measured. The base collar is not included.

In Table 2, the base collar was not included in the highlighted order of flexion/extension allowed, as this was expected to be higher due to the absence of contact with the shoulder/elbow. Table 2 also includes the maximum flexion and extension of the shoulder and elbow from Lorke *et al.*'s (2017) study on Beagle dogs for comparison and accuracy assurance.

Discussion

In this study, a comprehensive analysis was performed using several statistical methods, including a GLMM, three Kruskal Wallis with pairwise comparisons and a one-way ANOVA with post-hoc tests. Comparing the results, they differ, which is most likely due to the strengths of these tests and their abilities to work with outliers. Each test was performed to provide valuable insights; however, due to the flexibility and accuracy of the GLMM when handling large amounts of complex data, the discussion will focus on the results from the GLMM.

Reviewing the results of the GLMM, all six harnesses significantly reduced shoulder extension compared to the base collar. This finding disproves the hypothesis that there would be a significant difference in shoulder extension between the y-front and front-clip harness. However, because every harness impacted this angle, future research could remove the base collar to determine which harness has the least impact, as a collar may not always be an option for an owner (Bailey, 2022; Bolton *et al.*, 2021).

Exploring the front-clip harness, previously considered 'non-restrictive', (Zink, 2019) this harness significantly reduced all four angles measured (EE (132.1°), EF (76.4°), SE (84.7°), SF (84.1°)). The y-front harness also significantly reduced shoulder extension (SE) (93.5°) and flexion (SF) (88.9°) but had minimal impact on elbow extension (EE) (135.9°) and flexion (EF) (79.5°). Blake *et al.*, (2019) deem this impact to be caused by the y-front restricting the scapula angulation (Aspinall and Cappello, 2019), thus reducing movement.

Both the front-clip and y-front harnesses are manufactured with the strap running from the sternum to the dorsal neck, which could potentially influence biomechanics due to the loading on the sternum (Peham *et al.*, 2013). More research would be required to compare strap positioning and sternum impact. This harness design is thought of as being 'non-restrictive' due to the strap not crossing the chest; however, future research would be necessary to definitively prove which strap positioning has the least impact on biomechanics.

When comparing the elbow extension and flexion of the y-front and front clip, it is interesting that only one resulted in significant impact, as this potentially shows that the strap positioning is not the key factor in what influences flexion and extension. Due to the similar style, the other variables of lead position and strap width must be considered. More research is needed to focus on chest-strap width and its interference with elbow movement, as this may be the factor causing the difference in impact. The largest front-clip harness width is 4 inches at the widest part, compared to the largest y-front harness width being 1.5 inches at the widest part. Due to this large difference, it is possible that this factor would have an impact, but more research is needed to prove/disprove this.

The straight front allowed for the largest shoulder extension (93.8°) and flexion (89.6°), and the second-most elbow extension (134.6°), only significantly impacting shoulder extension (79.7°). Many studies have hypothesised that the 'non-restrictive' y-front harness would have less of an impact than the 'restrictive' straight-front harness (Pálya *et al.*, 2022; Sandberg, 2022), yet results have shown the opposite. Zink's (2019) study also found that the non-restrictive y-front significantly restricted shoulder extension when walking. Conclusions can be drawn that the straight front had the least impact on canine biomechanics, which is a key finding for the pet dog community as this may lessen the negative associations with this style (Julius K9, 2020b).

Furthering the comparison between straight-fronts and y-fronts, Pálya *et al.*'s. (2022) study compared the Julius K9 straight front to the new Julius K9 y-front. They found that both harnesses limited gait compared to a standard collar, but there was no significant difference between the two harness designs, thus showing a straight front is not necessarily 'restrictive' compared to a y-front. They concluded that movement restriction depends on the individual dog, and the fit of the harness, however expressed that future research would be needed to support this.

Clayton *et al.* (2017) completed equine research into saddle fitting, and discussed how saddles impact stride, velocity and acceleration. They stated that a poor-fitted saddle impairs the mobility of the horse's back, and inhibits a consistent gait, which can cause lameness and musculoskeletal issues in the long term. Linking this to pet dogs, if an owner struggles to fit a harness, it can impact their gait, which can cause issues over time. Future studies could see the ability of owners to fit different harnesses, and this could encourage brands to increase the harness-fit education they provide.

This research may aid in the safe production and scientifically informed harness advertisement and information to the public. It may also help dispel the incorrect beliefs around harness restriction. As discussed, the y-front harness is commonly sold as 'non-restrictive', but this study has proven that it restricts flexion and extension of both the elbow and shoulder, which is a misrepresentation to the buyers. Alternatively, the Julius K9, which is often labelled as 'restrictive' and is regularly disfavoured by animal professionals and the public, has been proven to have little impact on canine biomechanics. This also supports Julius K9's (2020a) statement regarding the safety and impact of their harness.

Results of this study found that the chest plate and step-in also significantly reduced shoulder extension (chest plate (88.5°), step-in (86.3°)) and flexion (chest plate (88.4°), step-in (87.6°)). However, both also significantly reduced elbow extension (chest plate (134.2°), step-in (133.9°)), but to a lesser degree. The step-in harness did significantly reduce elbow flexion (75.7°), whereas the chest plate did not (81.4°).

Focusing on the step-in harness, this harness has a similar design to the straight front, with the chest strap crossing the chest and shoulders. The Julius K9 straight front has a thicker chest strap that could have impacted gait less, due to the larger distribution of pressure, whereas the step-in chest strap is thinner, so pressure is distributed to a much smaller area. This could explain why the straight front had a much less impact on all measurements compared to the step-in. This refutes the hypothesis that predicted the step-in would have less impact than the straight front, and clearly demonstrates the need for future research to consider chest-strap width and its impact on biomechanics.

Peham *et al.* (2013) measured the pressure distribution of three straight-front guide dog harnesses with different chest-strap widths. They found that when the forelimb extended, the pressure force on the chest increased, but remained low when the forelimb was in flexion. They also found that the pressure force was lowest in the harness with the widest chest strap. Future research could involve similar research but using pet dogs to examine what width chest strap is optimum for low pressure force but still allows for standard flexion and extension.

Moving onto the no-pull harness; this is highly recommended for dogs that pull due to the tightening mechanism under the axilla (armpit), causing slight discomfort to the dog (Company of Animals, 2022). This harness has never been included in research, based on the authors' knowledge. The no-pull reduced all four angles measured: it significantly reduced shoulder extension (88.2°) and flexion (85.7°), and elbow extension (133.2°) and flexion (78.0°), but it reduced elbow extension to a lesser significant degree.

Coincidentally, both the y-front and the no-pull are produced by the brand Halti (VioVet, 2023), which is interesting that their no-pull had such a significant impact on biomechanics, whereas the y-front had very little impact. This demonstrates the requirement for future research to explore the different Halti-branded harnesses and compare how each influences canine gait, potentially supporting their future harness production.

Exploring all six harnesses, the hypothesis that a significant difference in biomechanics would be witnessed depending on the harness worn has been confirmed. However, based on the statistical data, the straight front had the least impact on canine gait, therefore is the authors' top recommendation.

As highlighted previously, there is a need for future research to focus on canine gait and harness impact (Blake *et al.*, 2019). Lafuente *et al.* (2018) discussed the necessity for future research to include multiple harness styles and brands. They also discussed the requirement of studies to include a researcher with experience surrounding dogs and physiology to improve the reliability of the results (Wang *et al.*, 2022). This study has confidently met both future research recommendations by including six harness designs and being controlled by an author with canine experience. Moreover, this study has overcome the limitations of previous studies by ensuring a larger sample size (Zink, 2019), a variety of breeds (Winter, 2013), and controlled extraneous variables, such as the influence of weather or treadmills (Lafuente *et al.*, 2018; Söhnel *et al.*, 2022).

The results of this study have been consistent with the results found by Lorke *et al.* (2017). Their data was included in Table 2 to demonstrate the maximum elbow and shoulder extension, and flexion achieved by healthy Beagle dogs during free movement. As results remained under the threshold identified by Lorke *et al.* (2017), and there is consistency within the ranges, this demonstrates a lack of anomalous data and suggests a high accuracy of the manual angles drawn in this study. Moreover, this suggests high concurrent validity due to the agreement between this study and Lorke *et al.* (2017).

Alongside this, internal consistency reliability has been assured, as results from each harness style have remained consistent (Salonen *et al.*, 2021). Both construct and content validity have also been upheld by ensuring the software used for analysis was specifically for biomechanics (Topál *et al.*, 2019), and that all angles were measured in the same way (Rocznik *et al.*, 2014).

Limitations and future research

The results and conclusions drawn from this study will provide invaluable information not only for pet dog owners, but for future researchers who wish to build on these findings. However, the author acknowledges the presence of some limitations within this study in order for others to build on these and provide essential future research.

Due to the time restraints within this study, only 30 dogs were included. While Ker and Ramalingam (2013) deemed this sufficient as the sample is significantly larger than other studies (Laverack *et al.*, 2021; Wiener and Haskell, 2016), the author identifies that a larger sample size would allow for investigation into the morphological differences between breeds (Carlisle *et al.*, 2019; Hecht *et al.*, 2019). This would allow for more specific harness recommendations for owners based on individual breed conformation (Voss *et al.*, 2011).

Due to the nature of a university setting, flexibility in study site was required. The author does not feel this affected the results; however, future studies should ensure site consistency (Desai, 2020). Although this study considered harness fitting and possible reactions to the researcher in the pre-trial questionnaire, it did not preassess the dogs' comfort level or experience of being walked on the lead by a stranger. To ensure ethicality, some dogs were walked by their owners to alleviate anxiety; however, future studies should ensure participants are comfortable with being handled by a stranger as part of the screening questions.

To help ensure reliability of results, the same researcher completed every manual angle measurement. However, as angular data was produced manually, there may be a level of unconscious or observer bias. Tanneberger and Ciupitu-Plath (2017) conclude that existing beliefs can impact the results drawn, as has been discussed above with Zink's (2019) study. To mitigate observer bias, future studies should involve multiple observers, as well as following blinding approaches if possible, meaning the researcher measuring the angle does not know which harness they are assessing. Alternatively, other researchers who are not well-informed in the field of harness study could be involved for angle measurements, so they do not have preconceived opinions on each harness.

Alternatively, markers could be used so Quintic Automatic Angle Measurement can be used, which may increase reliability (Engelsman *et al.*, 2022). If markers are used in future research, limitations with this technique such as lacking visibility on thick-furred dogs or movement alterations caused by the markers must be accounted for (Torres *et al.*, 2013).

The inclusion of other gair parameters, such as stride length, would strengthen these findings further (Torres *et al.*, 2017). Size difference and breed conformation impacts stride length, which could influence extension and flexion, so inclusion would add further clarity (Bliss *et al.*, 2022). Furthermore, comparisons of different gaits (e.g. hindlimb angles, or dogs at a trot) would provide further results. This would be especially relevant when researching the long-term effects of harnesses, as pet dogs vary their gait during standard walks (Kano *et al.*, 2016).

Longitudinal studies exploring the correlation between harness design and use and musculoskeletal disorders will help inform harness choices. Ethical considerations must be made here, as this study has shown the potential biomechanical influences of some harness designs (Murray *et al.*, 2021).

A final recommendation for future researchers is the consideration of a larger array of harnesses and brands available to pet owners. Analysis of the different styles within brands (e.g. the Julius K9 straight front and y-front), different brands within styles (e.g. Ruffwear y-front and Julius K9 y-front) and differing the attachment point (e.g. front clip and back clip) would deepen the understanding of harnesses and biomechanics. Focus on brands more/less readily available may result in shifts in the market, improving the knowledge of owners and widening their harness choices.

Despite the aforementioned limitations and requirements for future research, the results of this study are still valid and beneficial for the canine industry as a whole and provides the building blocks for students and researchers to study further into this field. Providing an accessible version for owners will impart clarity and enable them to make informed decisions. Hopefully, these results will drive the future of harness production to ensure for maximum safety and comfort for all dogs.

Conclusion

This study has concisely demonstrated that the choice of pet dog harness impacts biomechanics, closing the research gap into harness impact on canine flexion and extension in pet dogs. The results display the impact of each via angulation and have demonstrated how different harness styles impact shoulder and elbow extension and flexion.

Comparing results of all six harnesses, this study can confidently recommend the Julius K9 straight-front harness or the Halti y-front harness as the preferred option for pet owners. Furthermore, the highly regarded Ruffwear front-clip harness exhibited the largest impact on joint flexion and extension overall, thus illustrating its unsuitability. The author notes that while these harnesses were graded on suitability in results, the aim was not to conclude 'the best' harness overall; owners must use the information to select the best-suited harness for their individual dog.

Careful analysis of previous studies has allowed this study to accurately improve on previous limitations and draw updated conclusions on their findings. The study has demonstrated a need for further research to assess the impact of harness width on canine biomechanics. Research into breed differences will also help expand this area further.

These findings provide long-term benefits to the pet dog community. The inclusion of commonly available harnesses means that these conclusions are accessible for the average dog owner, and will help them to make informed decisions on their dogs' safety and wellbeing. This also provides appropriate alternatives and reassurance for those dogs for whom a collar is unsuitable.

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List of figures

List of tables

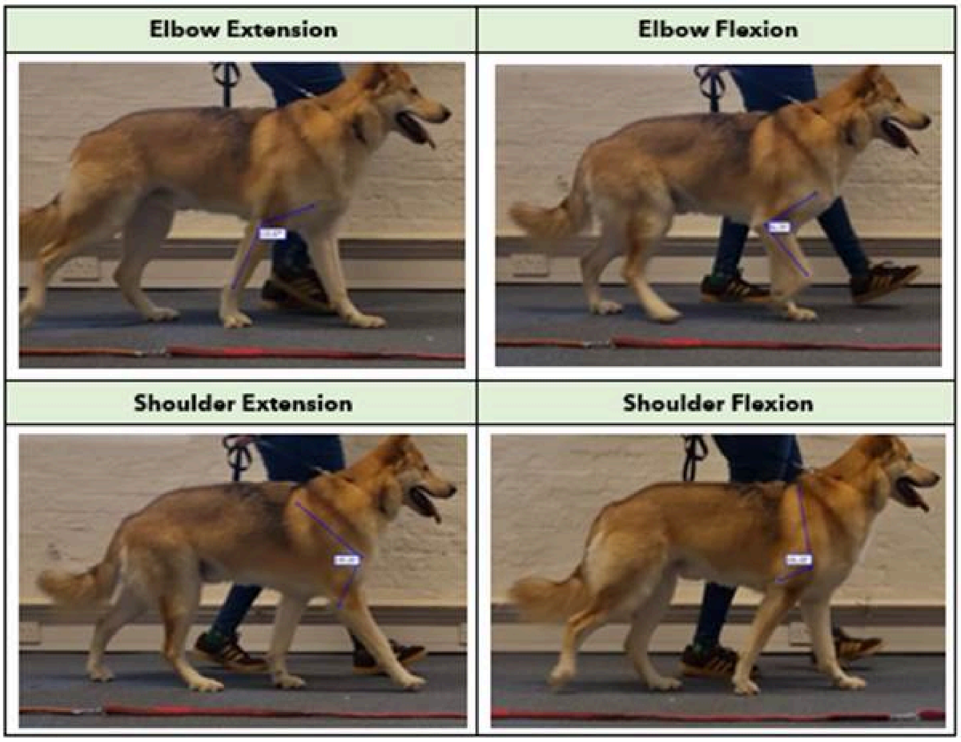
Appendix 1

Table A1: Harness brands, names, styles and images.

Harness Brand	Harness Name	Harness Style	Image of Harness
Julius K9	IDC© Powerharness	Straight front	
Ruffwear	Front Range© Dog Harness	Front-range	
EzyDog	Chest Plate Harness	Chest plate	
Halti	Comfort Collar	Base collar	
	No Pull Harness	No-pull	
	Walking Harness	Y-front	
3 Peaks	Step-In Harness	Step-in	

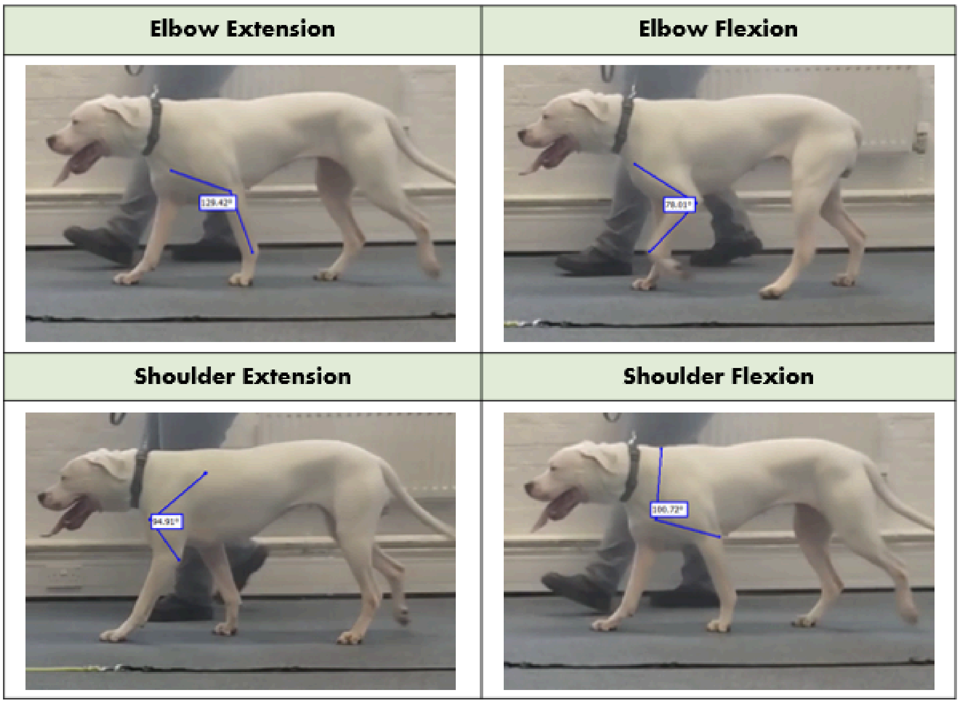
Appendix 2

Table A2: The four gaits measured



Appendix 3

Table A3: The four gaits measured



Appendix 4

Normality Tests for each harness/angle combination (28 in total)

This supplementary material provides the results from all 28 normality tests performed for each harness/angle combination. Although an omnibus normality test was performed overall, the individual results are concluded for additional information. The following table summarises the test statistics and p-values for each combination (all were analysed using a Shapiro-Wilk normality test).

Table A4: Normality tests performed for each harness/angle combination

Angle	Harness	Test Statistic (W)	P-Value	Comments
Elbow Extension	Base Collar	0.96129	p<0.01	Non-normal
Elbow Extension	Straight Front	0.96393	p<0.05	Non-normal
Elbow Extension	Front Clip	0.98338	p>0.1	Normal
Elbow Extension	Chest Plate	0.98373	p>0.1	Normal
Elbow Extension	Y-Front	0.97280	p>0.05	Normal
Elbow Extension	No-Pull	0.98833	p>0.1	Normal
Elbow Extension	Step-In	0.98822	p>0.1	Normal
Elbow Flexion	Base Collar	0.98283	p>0.1	Normal
Elbow Flexion	Straight Front	0.98947	p>0.1	Normal
Elbow Flexion	Front Clip	0.98160	p>0.1	Normal
Elbow Flexion	Chest Plate	0.96669	p<0.05	Non-normal
Elbow Flexion	Y-Front	0.98364	p>0.1	Normal
Elbow Flexion	No-Pull	0.97726	p>0.1	Normal
Elbow Flexion	Step-In	0.97162	p<0.05	Non-normal
Shoulder Extension	Base Collar	0.98547	p>0.1	Normal
Shoulder Extension	Straight Front	0.98047	p>0.1	Normal
Shoulder Extension	Front Clip	0.97633	p>0.05	Normal
Shoulder Extension	Chest Plate	0.97865	p>0.1	Normal
Shoulder Extension	Y-Front	0.96099	p<0.01	Non-normal
Shoulder Extension	No-Pull	0.97347	p>0.05	Normal
Shoulder Extension	Step-In	0.98783	p>0.1	Normal
Shoulder Flexion	Base Collar	0.98368	p>0.1	Normal
Shoulder Flexion	Straight Front	0.98531	p>0.1	Normal
Shoulder Flexion	Front Clip	0.98815	p>0.1	Normal
Shoulder Flexion	Chest Plate	0.97574	p>0.05	Normal
Shoulder Flexion	Y-Front	0.98522	p>0.1	Normal
Shoulder Flexion	No-Pull	0.99054	p>0.1	Normal
Shoulder Flexion	Step-In	0.98246	p>0.1	Normal

The normality tests indicate that although the majority of the data had a normal distribution, some were non-normally distributed showing significant deviations.

Appendix 5

Kruskal Wallis with pairwise Wilcox post-hoc for elbow extension

Due to there being non-normal data in the elbow extension results, a non-normal pairwise test is required, which is why a Kruskal Wallis with pairwise has been chosen. This shows comparisons between each collar/harness type.

Table A5: Comparisons between each collar/harness type using a Kruskal Wallis with pairwise (chi-squared = 28.57, df = 6, p<0.001)

	Base Collar	Str. Front	Front Clip	Chest Plate	Y-Front	No-Pull
Str. Front	1.00000	-	-	-	-	-
Front Clip	0.00295	0.00507	-	-	-	-
Chest Plate	1.00000	1.00000	0.00141	-	-	-
Y-Front	1.00000	1.00000	0.00339	1.00000	-	-
No-Pull	0.48788	0.74240	0.48788	0.48788	0.73307	-
Step-In	0.00166	0.00082	1.00000	0.00022	0.00070	0.17544

Appendix 6

Kruskal Wallis with pairwise Wilcox post-hoc for elbow flexion

Due to there being non-normal data in the elbow flexion results, a non-normal pairwise test is required, which is why a Kruskal Wallis with pairwise has been chosen. This shows comparisons between each collar/harness type.

Table A6: Comparisons between each collar/harness type using a Kruskal Wallis with pairwise (chi-squared = 42.87, df = 6, p<0.001)

	Base Collar	Str. Front	Front Clip	Chest Plate	Y-Front	No-Pull
Str. Front	1.00000	-	-	-	-	-
Front Clip	0.00073	0.05569	-	-	-	-
Chest Plate	0.54035	1.00000	0.07444	-	-	-
Y-Front	1.00000	1.00000	0.00307	1.00000	-	-
No-Pull	0.01488	0.54035	1.00000	0.87149	1.00000	-
Step-In	0.63946	1.00000	0.23166	1.00000	1.00000	1.00000

Appendix 7

Kruskal Wallis with pairwise Wilcox post-hoc for shoulder extension

Due to there being non-normal data in the shoulder extension results, a non-normal pairwise test is required, which is why a Kruskal Wallis with pairwise has been chosen. This shows comparisons between each collar/harness type.

Table A7: Comparisons between each collar/harness type using a Kruskal Wallis with pairwise (chi-squared = 50.89, df = 6, $p<0.001$)

	Base Collar	Str. Front	Front Clip	Chest Plate	Y-Front	No-Pull
Str. Front	0.20795	-	-	-	-	-
Front Clip	5.4e-06	0.00570	-	-	-	-
Chest Plate	0.00078	0.22826	1.00000	-	-	-
Y-Front	0.20795	1.00000	0.04041	0.51661	-	-
No-Pull	4.3e-06	0.01594	1.00000	1.00000	0.02093	-
Step-In	1.2e-05	0.02711	1.00000	1.00000	0.12960	1.00000

Appendix 8

One-Way ANOVA with Tukey's honest significant difference (HSD) test for shoulder flexion

Shoulder flexion had normal data for all harnesses/collars. Due to this, a normal pairwise test is required, which is why a One-Way ANOVA with Tukey's HSD test has been chosen. This shows comparisons between each collar/harness type.

Table A8: Comparisons between each collar/harness type using a Tukey's HSD test ($F = 9.02$, df = 6, $p<0.001$)

	Base Collar	Str. Front	Front Clip	Chest Plate	Y-Front	No-Pull
Str. Front	0.60419	-	-	-	-	-
Front Clip	0.00000	0.00016	-	-	-	-
Chest Plate	0.01801	0.69844	0.05449	-	-	-
Y-Front	0.15977	0.98634	0.00411	0.98594	-	-
No-Pull	0.00000	0.00437	0.98472	0.33900	0.05646	-
Step-In	0.00898	0.56080	0.09482	0.99999	0.95470	0.46886

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Glossary

Asymmetry: A lack of symmetry; differences in the behaviour of the limbs during movement.

Biomechanical: The study of mechanics and movement or structure of living organisms.

Brachycephalic breeds: dog breeds with flat faces and shortened snouts, which can lead to health problems.

Conformational disorders: Animals with exaggerated body shape, structure or appearance, which can negatively impact their health and welfare.

Gait: The pattern of steps of an animal at a certain speed or pace.

Gait analysis: the measurement of how the body moves during locomotion.

Generalised Linear Mixed Model (GLMM): a statistical regression model which is able to include randomeffects from different distributions.

Habituation: The decreased response to a certain stimulus after repeated exposure.

Kruskal Wallis: a nonparametric test which is rank-based which tests to see if there are statistical significant differences between two or more groups.

Longitudinal studies: A study that takes place over a long period of time; subjects are followed over time with either continuous or varied monitoring to see long-term impacts.

Markers: Reflective markers are placed on the subject; these are then tracked by cameras and used to create a 3D model of the subject's movement.

Morphological: Refers to the size, shape and structure of the body.

Non-restrictive harness: A harness that does not restrict movement.

Peak vertical force: The maximum force exerted perpendicular to the surface during stance phase.

Post-hoc test: A test used to analyse the results of an experiment with more than two groups to identify where the differences lie between the groups.

Restrictive harness: A harness that restricts movement in some way.

Straight front harness: this type of dog harness has a single, usually thick strap that goes horizontally across the dog's chest.

Tukey honest significant difference post-hoc: a test to see the significant differences between different groups.

Y-front harness: this type of dog harness has y-shaped straps that runs between the dog's front legs over the shoulder.

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