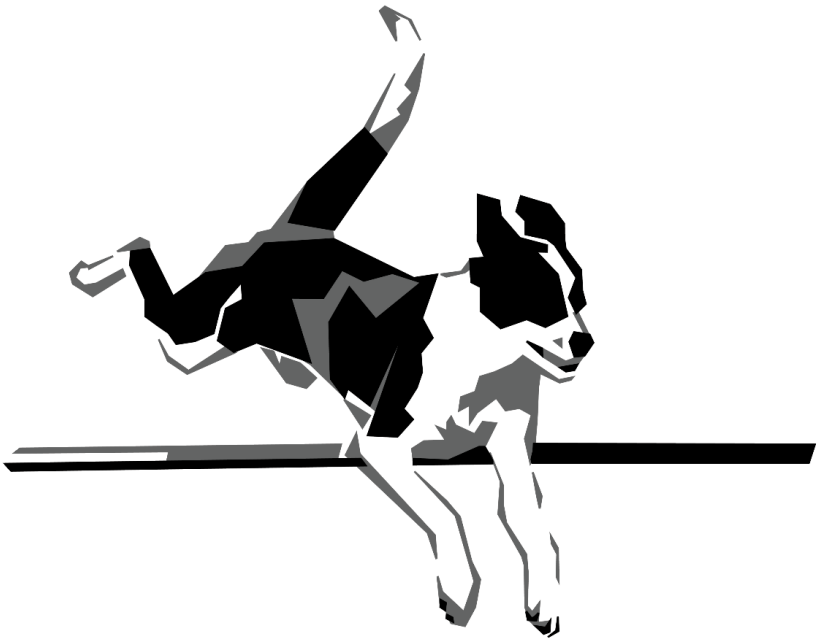
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The canine athlete: exploring the routines, injuries, and jumping biomechanics in agility dogs

Leena Inkilä



DOCTORAL DISSERTATION

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Abstract

Agility is one of the most popular canine sports in the world. It involves dogs navigating obstacle courses quickly and accurately under handler guidance. However, the involvement of animals in competitive sports has raised ethical concerns, necessitating research to assess and improve the welfare of sporting dogs. Survey studies indicate that approximately one-third of agility dogs suffer sport-related injuries, underscoring welfare concerns and the need for injury-prevention measures in agility. This study examines the impact of agility on canine athletes, focusing on sport-related routines, injuries, and jumping biomechanics.

Studies I and II were conducted using a retrospective survey on sport-related routines and injuries during one calendar year. Data was collected on competition-level Finnish agility dogs. Differences in training, competition, and management routines among 745 uninjured dogs were analysed across various height categories and competition levels. Details on injured anatomical locations, recovery, and injury contexts were collected from owners of 119 injured dogs. Regression models were used to identify injury risk factors. Study III assessed the biomechanics of jump take-off in 17 competing Border Collies across three bar heights (80%, 100%, and 120% of wither height). Dogs performed a straight-line sequence of three jumps, with the second jump's take-off being recorded. Ground reaction forces of fore- and hindlimb pairs were measured using force plates, while a three-dimensional motion capture system captured sagittal joint kinematics. The effect of bar height was analysed using a linear mixed model.

Finnish agility dogs generally begin training obstacle sequences at around one year of age. They typically train for agility once or twice a week and participate in two competition runs per month. Warm-up and cool-down routines are well-established in the sport. Structured conditioning exercises to improve strength, speed, endurance, or body control are typically performed only occasionally, if at all. However, dogs are usually walked for a median of 1.5 hours a day. Most dogs receive regular musculoskeletal care, such as massage or physiotherapy. Training, competition and management routines vary across different competition levels. Taller dogs are faster and jump higher bar heights relative to their wither height than smaller dogs.

Fourteen percent of dogs sustained an agility-related injury within one calendar year, and one-third had suffered an injury at some point during their agility career. Injuries to forelimbs and back were most common. Every tenth injury was career-ending. More than half of the injuries were reported to have occurred during obstacle performance, often due to collision, slip, or fall. Dogs with multiple previous agility-related injuries or high training frequency had higher odds of suffering an injury. Dogs with a moderate number of monthly competition runs had lower odds of injury.

Increasing the bar height led to biomechanical adaptations in the dogs' jumping performance, including greater vertical impulse and increased limb synchronisation.

Higher bar height resulted in lower horizontal velocity and steeper take-off angle. As the bar height increased, the range of motion increased in multiple limb joints through greater peak flexion or extension. Additionally, the number of strides between two jumps affected the biomechanics of take-off for the second jump.

These studies enhance our understanding of agility dogs' routines, injuries, and jumping biomechanics. The findings revealed that injuries were relatively common, even within a single calendar year, emphasising the importance of effective injury prevention measures. Minimising incidents like collisions, slips, and falls could reduce injuries and enhance the agility dogs' welfare. The biomechanical analysis showed that the higher bar heights led to a greater range of motion and more acute joint angles during weight bearing, potentially increasing tissue loads and injury risk. The production of increased vertical impulses at higher bar heights could lead to more rapid fatigue, which could contribute to injuries. However, the effects of increased speed at lower bar heights warrants additional research to fully assess the welfare effects of lower bar heights. The study identified risk factors that call for further investigation in prospective studies. This knowledge serves as a valuable resource for agility handlers, trainers, veterinarians, physiotherapists, and researchers.

List of abbreviations

AIC	Akaike information criteria
AKC	American Kennel Club
CCLR	Cranial cruciate ligament rupture
CPE	Canine Performance Events
FCI	Fédération Cynologique Internationale
GRF	Ground reaction force
ICC	Intraclass correlation coefficient
IQR	Interquartile range
LASSO	Least absolute shrinkage and selection operator
OR	Odds ratio
PVF	Peak vertical force
ROM	Range of motion
SE	Standard error
USDAA	United States Dog Agility Association

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List of original publications

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I Inkilä L, Hyytiäinen HK, Hielm-Björkman A, Junnila J, Bergh A, Boström A. Part I of Finnish Agility Dog Survey: Training and Management of Competition-Level Agility Dogs. *Animals*. 2022; 12(2):212. https://doi.org/10.3390/ani12020212

II Inkilä L, Hyytiäinen HK, Hielm-Björkman A, Junnila J, Bergh A, Boström A. Part II of Finnish Agility Dog Survey: Agility-Related Injuries and Risk Factors for Injury in Competition-Level Agility Dogs. *Animals*. 2022; 12(3):227. https://doi.org/10.3390/ani12030227

III Inkilä L, Boström A, Valadão P, Avela J, Walker S, Mäkitaipale J, Bergh A, Hyytiäinen HK. Effect of bar jump height on kinetics and kinematics of take-off in agility dogs. *Submitted to PLOS ONE*. 2024.

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1 Introduction

Dogs have shared an unparalleled bond with humans for thousands of years, playing integral roles in our societies in companion and working roles. One of the notable manifestations of the human-dog partnership in recent decades has been the rise of canine sports that rely on cooperation between dog and handler, such as agility, rally-obedience, and nose work.

Agility was first presented in 1978 as a demonstration to amuse spectators at the Crufts dog show (Fender, 2004). The Kennel Club of United Kingdom established the first regulations for these dog jumping competitions in 1980 (Fender, 2004). Unchanged until today, agility involves dogs navigating an obstacle course as fast as possible with accurate performance of the obstacles, while the andler guides the dog to the route. Popularity of agility has grown since then. There were 140 00 agility competition performances (runs) in 2023 in Finland, and over 1.1 million agility runs were competed in 2022 in a single organisation in the United States (US) (American Kennel Club, 2022; Suomen Kennelliitto, 2024).

Ethical concerns have emerged regarding animals in sports, potentially impacting community approval, also termed the social license to operate. For example, concerns about welfare issues such as race injuries and euthanasia of surplus dogs have resulted in banning or regulating the greyhound racing industry (American Veterinary Medical Association, 2018; Hampton et al., 2020; NSW Government, 2023; UK Legislation, 2010). Research on sporting dogs is essential to evaluate the current state of their welfare. Indeed, lack of scientific research and transparent monitoring practices, despite the long-term welfare concerns, may have affected the erosion of the social license of greyhound racing industry (Hampton et al., 2020). Use of animals in sport may be justifiable from the perspectives of many ethical theories if negative welfare effects are minimised, positive welfare effects are maximised, risks are mitigated, and regulations are followed (Campbell, 2023). Research can identify areas for improvement and develop tools and standards to enhance the welfare of sporting dogs.

The Five Domains Model for animal welfare comprises nutrition, physical environment, health, behavioral interactions, and mental state (Mellor et al., 2020). Many of these aspects may be affected by the agility sport: for example, the care and management of agility dogs may differ from pet dogs. The importance of the dogs experiencing positive affective states, in addition to freedom from negative affective

states, has been raised in past decades (Mellor et al., 2020). It is likely that training agility can provide positive interactions with humans if the training methods are based on positive reinforcement and the dogs' voluntary engagement (Cobb et al., 2021; Mellor et al., 2020). However, one of the hazards of agility for canine welfare is injuries caused by the sporting activity. According to owner reports, roughly one third of agility dogs suffer a sport-related injury (Cullen et al., 2013a; Evanow et al., 2021; Jimenez et al., 2022), suggesting that many agility dogs are impacted.

Injury prevention and the improvement of canine welfare are also important to the people involved in agility (Sellon et al., 2023). Factors influencing the injuries are not fully understood, and strategies to prevent injuries and decrease physical loads associated with the sport are based merely on anecdotal evidence. For example, heights of the jump obstacles have been debated and bar heights decreased in competitions, although the scientific evidence on effects of bar heights on jumping biomechanics and injuries is sparse.

Evidence-based recommendations for prevention of injuries cannot currently be given due to the limited scientific research on agility dogs. This research investigates the effects of agility sport on the canine athletes, focusing on the physical welfare aspects including sport-related routines, injuries, and jumping biomechanics, and discusses the steps towards effective injury prevention strategies.

2 Review of the literature

2.1 Agility sport

Agility is a canine sport in which the handler guides the dog through an obstacle course as fast as possible in a predetermined order and without faults on the obstacles. The dog performs various types of obstacles including tunnels, weave poles, contact obstacles (dogwalk, A-frame, and seesaw) and various types of jumps (bar jump, tyre, wall, spread jump, and long jump). Each course consists of 15 to 22 obstacles (Figure 1), with a minimum of seven obstacles being jumps according to the Fédération Cynologique Internationale (FCI) regulations (Fédération Cynologique Internationale, 2023). Approximately 65% of the obstacles in each course are bar jumps in practice (Cullen et al., 2013a). The length of the dog's route is 100 to 220 meters per course (Fédération Cynologique Internationale, 2023), but information on average speed of the agility dogs' average speed is lacking. Each course is unique with level-appropriate challenges and is planned by an agility judge to test the handlers' and dogs' skills. Dogs must navigate the obstacles according to the regulations and as fast as possible, requiring taught skills and athletic capabilities, such as speed, strength and flexibility, while following the route communicated by the handler's physical and verbal cues. A single performance of the course is called a run. Besides the regular agility courses, there are related agility sports, gamblers and snookers, where the handlers plan their own course around the obstacle field to collect points according to the rules (United States Dog Agility Association, 2011).

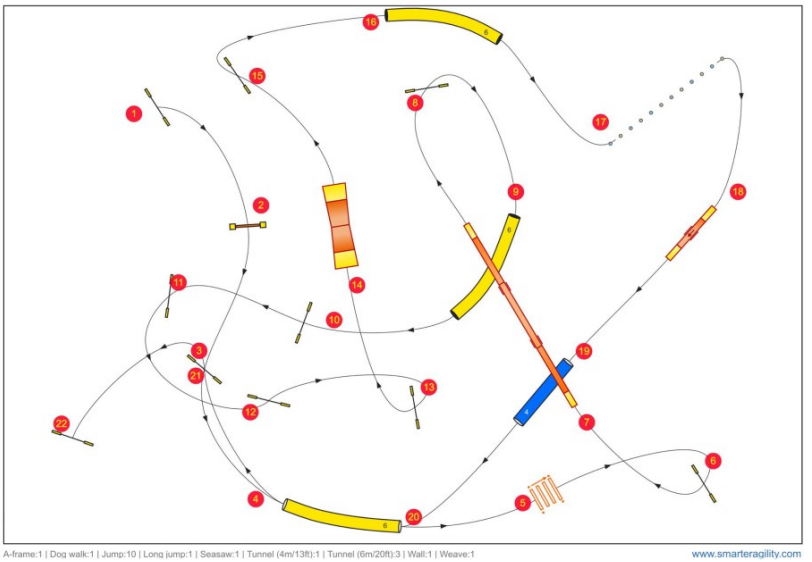


Figure 1 Example of an agility course plan for the A3 class (highest class) used in competition in Europe in 2024. Course planned by Stefanie Semkat.

2.1.1 Height categories and bar heights in agility

Agility is a popular sport worldwide with multiple organisations setting regulations. FCI regulations in Europe are used in two major international competitions: FCI World Championships and European Open. National regulations in European countries typically largely follow those of FCI, but some variation occurs, for example, in dogs' height categories. North America has multiple organisations, with some of the most popular being the American Kennel Club (AKC), Canine Performance Events (CPE) and United States Dog Agility Association (USDAA) (Sellon et al., 2023).

All the above-stated organisations divide the dogs into height categories based on their wither height. The number and cut-offs of height categories vary among organisations, as does the height of jump obstacles (bar height) for each height category (Table 1, Figure 2). The proportional bar height is generally 70–120% of a dog's wither height (Table 1). The highest relative bar heights are observed in the European organisations, where the dogs in the lower range of the 'large' category jump up to 120–125% of wither height and 10–12 cm above wither height. Dogs do not jump more than 5 cm above their wither height in the major North American organisations, AKC, CPE, and USDAA. Additionally, these organisations offer optional lower bar heights. However, handlers in AKC competitions may opt to have their dogs jump higher bar heights.

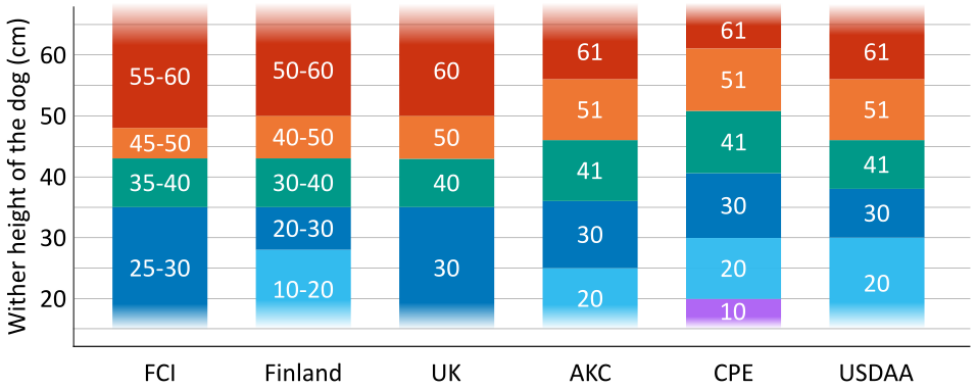


Figure 2 Height categories in selected agility organisations in Europe and North America. Different colours represent different height categories; white numbers represent the bar height in each category. Optional, lower or higher bar heights are not presented in this figure. FCI = Fédération Cynologique Internationale, UK = United Kingdom (national regulations from the Kennel Club), AKC = American Kennel Club, CPE = Canine Performance Events (United States), UDSAA = United States Dog Agility Association.

Bar height is a highly debated subject in the sport. New height categories have been introduced and/or bar heights reduced during the past 10 years in all major organisations. For example, the maximum bar height was reduced in FCI regulations by 5 cm for each category in 2018: 'large' category dogs jumped up to 65 cm prior to 2018 and now jump a maximum of 60 cm bar height (Fédération Cynologique Internationale, 2018). FCI introduced 'intermediate', a fourth height category, in 2018, which consists of dogs that previously competed in the 'large' category, reducing the bar height for these dogs (Fédération Cynologique Internationale, 2023). The reduced maximum bar height and a fourth height category has also been added to national regulations in Europe with some countries additionally introducing a fifth height category of 'extra small' for the smallest dogs. Recent updates to bar heights and/or height categories, towards reduced bar heights, have also been made in the AKC and USDAA (Table 1) (American Kennel Club, 2017; USDAA, 2021). The scientific knowledge regarding the effects of bar height is sparse; thus, these regulation changes have been based merely on anecdotal evidence.

Table 1 Height categories, bar heights and minimum age in competitions of selected agility organisations.

Inches are transformed into centimeters.

[a] Calculation of upper range for smallest category and lower range for largest category is not possible, because minimum and maximum wither heights are unknown. [b] Maximum difference cannot be defined for smallest category because minimum wither height is unknown. [c] Upper range of proportional bar height and maximum difference increase if owner utilises the option to enter dog into a higher height category. [d] Upper and lower range of proportional bar heights and the maximum difference between wither and bar heights decrease when owner enters optional classes in which bar heights are lower.

Organisation (country)	Height categories	Wither height	Bar height	Proportional bar height[a]	Max difference between wither and bar heights[b]	Minimum age	Other
FCI (Europe)	Small	<35 cm	25–30 cm	72 % – undefined	Undefined	24 months for international agility competitions. 18 months for national agility competitions.	Used for international FCI competitions. National regulations may differ.
	Medium	≥35 cm, <43 cm	35–40 cm	82–114 %	5 cm		
	Intermediate	≥43cm, <48 cm	45–50 cm	94–116 %	7 cm		
	Large	≥48 cm	55–60 cm	Undefined – 125 %	12 cm		
Finnish Agility Association (Finland)	Extra small	<28 cm	10–20 cm	36 % - undefined	Undefined	18 months	Handlers of dogs ≥48 cm but <50 cm can choose to compete in either 'small large' or 'large' category.
	Small	≥28 cm, <35 cm	20–30 cm	57–107 %	2 cm		
	Medium	≥35 cm, <43 cm	30–40 cm	70–114 %	5 cm		
	Small large	≥43 cm, <50 cm	40–50 cm	80–116 %	7 cm		
	Large	>50 cm	50–60 cm	Undefined – 120 %	10 cm		
Kennel Club (United Kingdom)	Small	≤35 cm	30 cm	86 % – undefined	Undefined	18 months	
	Medium	>35 cm, ≤43 cm	40 cm	93–114 %	5 cm		
	Intermediate	>43 cm, ≤50 cm	50 cm	100–116 %	7 cm		
	Large	>50 cm	60 cm	Undefined – 120 %	10 cm		

Organisation (country)	Height categories	Wither height	Bar height	Proportional bar height[a]	Max difference between wither and bar heights[b]	Minimum age	Other
American Kennel Club (United States) [c,d]	8 inches	≤25 cm	20 cm	80 % – undefined	Undefined	15 months	Bar heights in Preferred class are 10 cm lower.
	12 inches	≤36 cm	30 cm	86–120 %	5 cm		
	16 inches	≤46 cm	41 cm	89–114 %	5 cm		Handlers may opt to enter in higher height category.
	20 inches	≤56 cm	51 cm	91–111 %	5 cm		
	24 inches	>56 cm	61 cm	Undefined – 109 %	5 cm		
Canine Performance Events (United States) [d]	4 inches	≤20 cm	10 cm	50 % – undefined	Undefined	15 months	Bar heights in Veterans and Enthusiast class are 10 cm lower and in Specialist classes 20 cm lower, with the exception that 10 cm is the lowest possible bar height.
	8 inches	>20 cm, ≤30 cm	20 cm	67–100 %	0 cm		
	12 inches	>30 cm, ≤41 cm	30 cm	75–100 %	0 cm		
	16 inches	>41cm, ≤51 cm	41 cm	80–100 %	0 cm		
	20 inches	>51 cm, ≤61 cm	51 cm	83–100 %	0 cm		
	24 inches	>61 cm	61 cm	Undefined – 100 %	0 cm		
United States Dog Agility Association (United States) [d]	Extra small	≤30 cm	20 cm	67 % – undefined	Undefined	14 months for Intro program. 18 months for other programs.	Bar heights of Performance program are 10 cm lower. Veteran and Intro programs have lower bar heights.
	Small	>30 cm, ≤38 cm	30 cm	80–100 %	0 cm		
	Medium	>38 cm, ≤46 cm	41 cm	89–106 %	2 cm		
	Large	>46 cm, ≤56 cm	51 cm	91–111 %	5 cm		
	Extra Large	>56 cm	61 cm	Undefined – 109 %	5 cm		

2.1.2 Agility dogs

A variety of dog breeds compete in agility. The Border Collie is the most common breed in agility across studies (Cullen et al., 2013a; Evanow et al., 2021; Levy et al., 2009; Pechette Markley et al., 2021). Other popular breeds include Shetland Sheepdog, Australian Shepherd, and mixed breed (Cullen et al., 2013a; Evanow et al., 2021; Levy et al., 2009; Pechette Markley et al., 2021). The mean height of agility dogs in a large survey sample was 46 cm and weight 16.6 kg (Sundby et al., 2022). Female and male dogs have been relatively equally presented in surveys on agility dogs (Evanow et al., 2021; Jimenez et al., 2022; Pechette Markley et al., 2021).

Most agility dogs have been acquired from a breeder (74% of agility dogs) and with agility in mind (71%) (Sundby et al., 2022), suggesting that traits beneficial in agility might be preferred in breeding selections. Agility was the main sport focus for 72% of agility dogs in a recent survey (Sundby et al., 2022). However, these proportions may represent the owners who are willing to respond to surveys and not necessarily the actual variation among the sport participants.

2.1.3 Sport-related routines for management, training, and competing

Knowledge is needed on training and competition routines to fully understand the physical demands of agility. Information on typical training and competing frequencies aids owners, trainers, veterinarians, physiotherapists, and other professionals to understand what these dogs should be prepared for. Agility dogs generally live as pets in their owner's home, but their management is likely to differ from typical pet dogs. The dogs need to have the required physical condition (e.g., strength, flexibility, and endurance), gained through activities both outside and on the agility field, to perform safely and successfully in agility. Reports on the management, training and competition routines of agility dogs are sparse: information is offered mainly by injury risk studies and covers North American agility dogs almost exclusively (Cullen et al., 2013b; Evanow et al., 2021; Kerr, Fields, et al., 2014; Pechette Markley et al., 2022; Sellon & Marcellin-Little, 2022).

2.1.3.1 Early agility career

Training of young agility dogs is often debated. In an international, mainly North American, sample by Pechette Markley et al. (2022), half of the dogs had started agility-specific training between four and 12 months of age (Figure 3) (Pechette Markley et al., 2022). Training of low jumps was began typically at seven to 12 months, and competition heights were jumped after one year of age – in one-third

of the dogs after 18 months (Pechette Markley et al., 2022). The age at which contact obstacles and weave poles were performed varied but was beyond 12 months for the majority of dogs (Pechette Markley et al., 2022).

A study by Pechette Markley et al. (2022) assessed the relationship between orthopaedic conditions and the age at which dogs began training for various obstacles (Pechette Markley et al., 2022). All orthopaedic conditions resulting in time off from agility were recorded, regardless of the perceived cause (Pechette Markley et al., 2022). The risk of developing orthopaedic conditions was higher in agility dogs that started jump training at a younger age. Compared to dogs that started any jump training after 18 months, agility dogs that started at 3-12 months had over twice the odds of developing an orthopaedic condition, while those that started at 13-18 months had over 1.5 times higher odds (Pechette Markley et al., 2022). Starting seesaw training before 10 months and starting weave training at 10–12 months were, interestingly, associated with lower risk compared to starting after 18 months.

It is possible that some tasks may improve physical condition, such as coordination, in beneficial ways, while jump training as a puppy may negatively impact the immature musculoskeletal system in the short or long term. However, there might have been other, uncontrolled factors that were more common among dogs that started jump training early, such as the Border Collie breed or the handler's competitiveness, which also increase the odds of injury in agility dogs (Evanow et al., 2021; Pechette Markley et al., 2022; Sellon et al., 2018; Sellon & Marcellin-Little, 2022; Sundby et al., 2022). So far, other studies have not investigated the effect of training on young agility dogs.

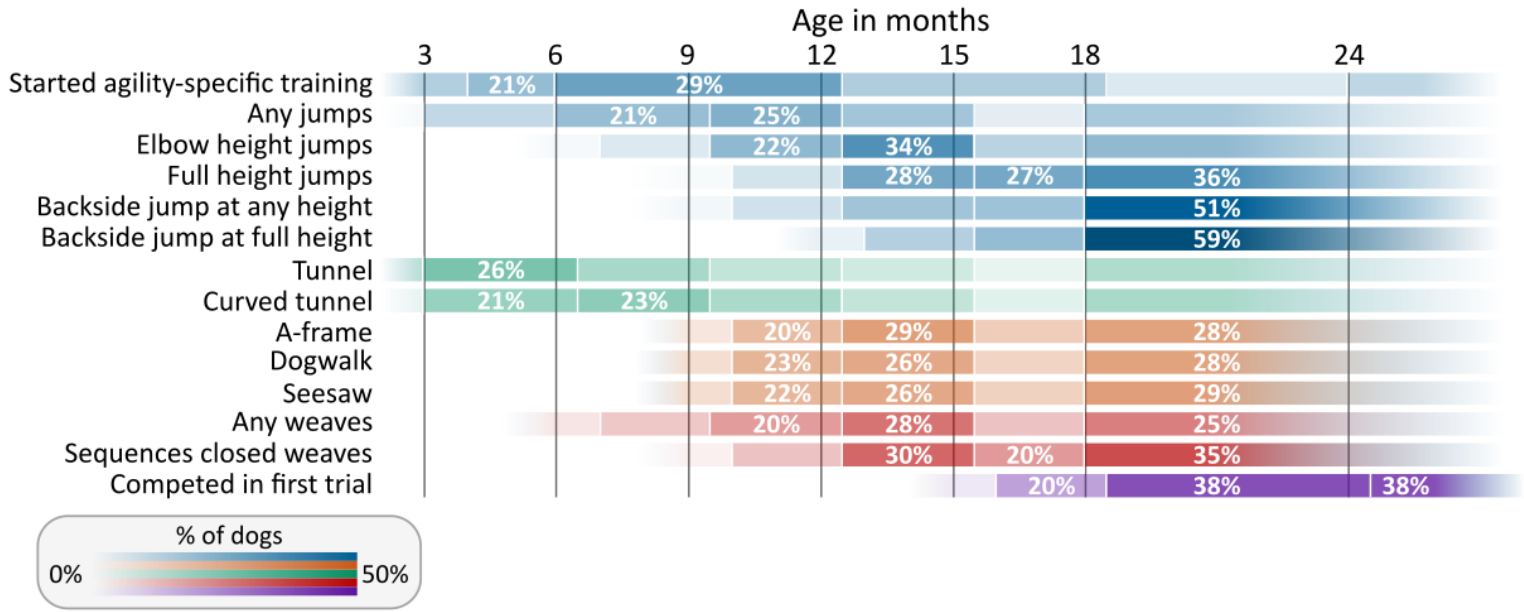


Figure 3 Starting ages for various agility-related tasks. Illustration is based on information provided by Pechette Markley et al. (2022). Shading of the sections indicates the percentage of dogs starting at that age with darker colours illustrating higher percentages. Numbers are additionally shown for age classes with >20 % of dogs. Cut-offs of age categories varied between variables in the article by Pechette Markley et al. (2022).

2.1.3.2 Agility training routines

Detailed information on agility training routines is lacking. A study from 2013 reported that over 70% of the studied dogs were trained more than once a week (Cullen et al., 2013b). More recent studies from 2022 reported that 90% of agility dogs trained agility 1–7 times a week (Sellon & Marcellin-Little, 2022), or 80% trained up to three times a week (Jimenez et al., 2022). Another study from the US provided a mean of 2.5 training sessions per week (Dinallo et al., 2017). Studies are difficult to compare due to the different categorisations of training frequency (e.g., different cut-offs for categorical variables), but it seems likely that the typical training frequency is around 2–3 times a week. One study reported training frequency to be associated with competition level: Dogs in the highest classes trained the least (Dinallo et al., 2017), but this has not been evaluated in further studies.

Training session duration has been reported to be up to 30 minutes for half of the dogs and 30–60 minutes for over 40% of dogs (Jimenez et al., 2022). Close to 90% of dogs trained a total maximum of two hours of agility a week, with the remaining 10% training more (Kerr et al., 2014). A definition of training time was not offered in these studies and, thus, it remains unknown whether warm-up, waiting time or cool down has been included or whether only active time performing in agility was counted as training time.

The training load is determined not only by frequency and duration of training sessions but also by the training intensity, which has not been provided in the current literature. Additionally, all studies are based on retrospective surveys with no studies using a more detailed prospective design or objective measures of activity. Furthermore, it is likely that the training load varies not only across weeks or months but also across individual dogs. A North American study reported that 85% of dogs trained 10-12 months/year with the remaining 15% having at least a couple of months off from the sport a year. Some owners may additionally periodise training to achieve peak conditions at main competition events, because planning around a big event has been reported (Pechette Markley et al., 2022).

2.1.3.3 Competition routines

Competition routines in agility are another important factor to consider. In a sample collected from participants at agility events in United States, dogs attended a mean 20 events per year, each event typically consisting of two competition days with three to four runs a day (Evanow et al., 2021). Other studies have reported a similar or lower number of competitions per year (Dinallo et al., 2017; Jimenez et al., 2022; Pechette Markley et al., 2022; Sellon & Marcellin-Little, 2022). Dogs competing in higher classes compete more than beginner dogs (Dinallo et al., 2017).

Competitions appear to contribute to the physical load of agility dogs – especially in the high-level dogs, at least in North America.

2.1.3.4 Sport surfaces

Various surfaces are used in agility, yet little is known about their effects on the dogs. The surfaces most used for agility training and competitions in North American samples are natural grass, (82–85% of dogs), artificial turf (51–60%) and dirt (35–62%) (Jimenez et al., 2022; Pechette Markley et al., 2022). Other relatively commonly used surfaces include sand, rubber mat, and foam mat (Jimenez et al., 2022; Pechette Markley et al., 2022). Some dogs run on multiple surfaces (Jimenez et al., 2022).

Jimenez et al. (2022) asked agility dog owners to rate their dog's performance on different surfaces. Natural grass received the best rating, followed by artificial turf and dirt. Additionally, the handlers' observations of markers of decreased performance on different surfaces were collected. They included, for example, slipping prior to jump take-off, shoulder- or face-plant at jump landing, knocking more bars than usual, slipping at tunnel entries or exits, slower times than usual, shortened stride length, and increased soreness after training or competition. Owners had observed the fewest of these markers on natural grass. Only dirt was not significantly worse than natural grass. The highest number of these performance deficits were observed on rubber mat, significantly more than on natural grass, artificial turf, sand, dirt, or foam mat, suggesting that rubber mat was the least suitable for the sport. (Jimenez et al., 2022)

2.1.3.5 Warm-up and cool-down

Structured neuromuscular warm-up programs have been shown to reduce the risk of multiple types of injuries in different sports and age groups in humans (Ding et al., 2022; Herman et al., 2012; H. Zhang et al., 2022). Additionally, warm-up improves performance such as sprint speed or vertical jump height in humans (Fradkin et al., 2010; Silva et al., 2018).

The effect of warm-up is very sparsely investigated in dogs. Muscular efficiency of *m. triceps brachii,* measured with acoustic myography, has been reported to improve after five minutes of structured warm-up in agility dogs, but no effects were observed in *m. gluteus superficialis* (Fuglsang-Damgaard et al., 2020). According to two surveys from 2013–2014, 85–88% of agility dogs are warmed up before agility and 57% are stretched (Cullen et al., 2013b; Essner, Hesbach, et al., 2022; Kerr, Fields, et al., 2014). A typical duration of 1-20 minutes has been reported with warm-ups consisting most commonly of a general warm-up (walk or trot) and mobility exercises (e.g., play, tricks, exercises with increased range of motion, off-

leash exercise or intervals of canter) (Essner, Hesbach, et al., 2022). Warm-up before agility is not associated with reduced injury risk (Cullen et al., 2013b; Kerr, Fields, et al., 2014). However, both studies looking at this used a retrospective design without knowledge of warm-up routines before the injury.

Active cool-down, low- to moderate-intensity exercise after training, appears to be ineffective in improving recovery or reducing injury risk in humans (Van Hooren & Peake, 2018). Removal of blood lactate is enhanced with active cool down compared to passive cool down, but it does not improve subsequent performance (Nédélec et al., 2012; Weltman & Regan, 1983). Nevertheless, active cool down has been recommended for canine athletes (Zink & Carr, 2018). About 60% of agility dogs are cooled down and one-fourth are stretched after agility with no association to reduced or increased injury risk (Cullen et al., 2013b; Kerr, Fields, et al., 2014).

2.1.3.6 Musculoskeletal care and physical conditioning

According to one North American survey, musculoskeletal care, such as massage, chiropractic treatment or acupuncture, is given to 60% of agility dogs (Cullen et al., 2013b). In another survey, 40% of agility dogs visited a chiropractor, 24% a massage therapist and 12% an acupuncturist (Kerr, Fields, et al., 2014). These treatments may be used for preventative care or to treat injuries. It remains unknown how often these treatments are typically given and whether the same professionals and treatment modalities are used outside North America.

Physical training is often a key part of an athlete's training program in human sports. For example, strength training both improves performance and decreases risk of injury in many sports (Lauersen et al., 2014; Lesinski et al., 2016; Seitz et al., 2014; H. Zhang et al., 2022). About 70–75% of agility dogs do some conditioning exercise to improve aerobic, strength, balance, or proprioception (Cullen et al., 2013b; Sellon & Marcellin-Little, 2022). Of Swedish agility dogs, 40% performed exercise to improve musculoskeletal fitness, and 30% performed exercises that improved both cardiorespiratory and musculoskeletal fitness (Essner, Hesbach, et al., 2022). Conditioning exercises should be performed frequently to have an effect. A quarter of the dogs did core strength, balance, stretching, or body awareness exercises at least three times a week in a North American sample (Sellon & Marcellin-Little, 2022), without further details on these exercises.

Serum lactate concentration rises above the anaerobic threshold after performing two competition-length agility courses (Rovira et al., 2007). Increased aerobic fitness reduces lactate concentration after the same absolute intensity exercise in dogs (Banse et al., 2007). Improved aerobic fitness enhances recovery from high-intensity intermittent exercise in humans (Tomlin & Wenger, 2001). Thus, a certain levels of aerobic fitness is also likely to be beneficial for agility dogs – especially in training sessions that can take over half an hour (Jimenez et al.,

2022). Walks with the owner are part of pet dogs' everyday lives and probably influence the dogs' aerobic fitness to a point. Three-quarters of agility dogs are walked less than two hours a week (Kerr, Fields, et al., 2014). Roughly 60% of agility dogs are taken on longer walks (>30 min.) a maximum of two times of week in another survey, with one-third receiving long walks less often than weekly (Sellon & Marcellin-Little, 2022). The benefit of walks on the aerobic fitness of these agility dogs might be limited at the just-mentioned levels. However, over 70% of Swedish agility dogs have at least one hour of non-sport-specific physical activity each day (Essner, Hesbach, et al., 2022), which is likely to have a greater effect. Aerobic fitness in humans can alternatively be improved by short bouts of intensive exercise instead of endurance training (Gist et al., 2014). Thus, agility training as such may improve aerobic fitness as well.

Aerobic fitness of Border Collies competing in agility has been evaluated by determining the heart rate deflection point during an incremental exercise test (Radin et al., 2015). The heart rate deflection point correlates with the lactate threshold (also called anaerobic threshold) in dogs – determining the point where lactate accumulation exceeds the removal or metabolism of lactate (Restan et al., 2019). However, there has been some controversy about the connection between the two measures in humans (Bodner & Rhodes, 2000). The heart rate deflection point of agility Border Collies was not compared to non-agility dogs (Radin et al., 2015). However, the point occurred at a similar running velocity with Beagles that were described as fairly sedentary, and the maximum velocity tolerated in the test was close to Beagles as well (Restan et al., 2019). This suggests that the aerobic fitness of these agility dogs may not have been particularly good. Nevertheless, the incremental exercise tests were not identical, and the protocol is known to affect the heart rate deflection point (Bodner & Rhodes, 2000). The exercise and training routines of the agility dogs were not described. The knowledge of how aerobic fitness affects performance or injury risk in agility dogs is lacking.

2.2 Injuries in agility dogs

Multiple survey studies have investigated injuries in agility dogs. These surveys are based on owners rating their agility dogs either as injured or non-injured, which is a major limitation of these studies because owners may perceive and define injury differently as well as have varying capabilities to notice clinical signs. Many agility dog surveys have not, to my knowledge, offered a detailed definition of an injury in the survey (Cullen et al., 2013a; Evanow et al., 2021; Jimenez et al., 2022). Two studies have used a time-loss definition, including injuries to the dog that resulted in discontinuation of training or time-off training (Levy et al., 2009; Pechette Markley et al., 2021). None of the surveys have required veterinary records to be submitted and, thus, all rely on owner reports (Cullen et al., 2013a; Evanow et al.,

2021; Jimenez et al., 2022; Kerr, Fields, et al., 2014; Levy et al., 2009; Pechette Markley et al., 2021).

Some studies have included only injuries that owners consider to be agility-related (Cullen et al., 2013a; Evanow et al., 2021; Jimenez et al., 2022; Kerr, Fields, et al., 2014; Levy et al., 2009). The prevalence of agility-related injuries is 28–45% of agility dogs when all injuries in the entire career as of the time of survey participation are included (Cullen et al., 2013a; Evanow et al., 2021; Jimenez et al., 2022). One-third of agility dogs had injured themselves within a two-year period and 8% within three months when agility-related injuries within a limited period prior to survey participation have been studied (Kerr, Fields, et al., 2014; Levy et al., 2009). The number of injuries should preferably be related to exposure time to allow for comparison of injury risks and a better understanding of the extent of the problem (van Mechelen et al., 1992). So far only one study has calculated the injury rate, relating the number of injuries to exposure: 1.72 injuries are reported per 1000 competition runs and 1.74 per 1000 training hours (Kerr, Fields, et al., 2014).

Irrespective of injury cause, 64% of agility dogs have had some injury (including all body systems, e.g., muscular, dermatologic and digestion) (Essner et al., 2024), and 42% of agility dogs have had an orthopaedic condition causing time loss from the sport (Pechette Markley et al., 2021). The cause of the injury was not considered in these studies, resulting in inclusion of non-agility-related injuries as well. Thus, prevalence of all injuries in a sample of agility dogs is indicative of their general health but does not directly inform about the effects of agility.

Only one study has compared injury risk in agility to other canine sports (obedience, rally-obedience, and utility trials): in the multivariate model, risk of injury was not higher among agility dogs compared to other sport dogs when controlling for breed, age and other factors (Essner et al., 2024). Other studies have reported injuries and orthopaedic conditions in other sporting dogs. The prevalence of sport-related injuries is 34–39% in flyball dogs (Montalbano et al., 2019; Pinto et al., 2021) – similar to prevalence reported in agility dogs. Gundogs, working farm dogs and racing greyhounds appear to have higher rates of injuries than agility dogs (Houlton, 2008; Isaksen et al., 2020; Palmer et al., 2021). However, the definitions of injuries, data collection methods and samples (e.g., age, breed) vary greatly, making it very difficult to compare results between studies. Looking at the current and very limited evidence, the agility dogs' injury risk does not appear to be higher than in other canine sports or working dogs.

2.2.1 Causes of injury

The competition-related injuries are equally or sometimes more common than injuries related to agility training in many studies (Cullen et al., 2013a; Kerr, Fields, et al., 2014; Levy et al., 2009). However, training injuries were more common (65%

of reported injuries) in the most recent study (Jimenez et al., 2022). Owners often consider the injury to occur in direct contact with, due to a fall from, or otherwise in association with an obstacle (32–64% of injuries) (Jimenez et al., 2022; Kerr, Fields, et al., 2014; Levy et al., 2009). Table 2 presents obstacles involved in injuries.

The bar jump, the most common obstacle on the course, is often associated with injury without further information on what has happened during the jump (Cullen et al., 2013a; Jimenez et al., 2022). Older studies commonly reported A-frame and dogwalk as injury related (Cullen et al., 2013a; Levy et al., 2009), but in a more recent study their proportion was somewhat lower than previously reported (Table 2) (Jimenez et al., 2022). Additionally, the percentage of injuries associated with a tyre appears to have decreased, whereas injuries during weaves and open tunnels seem to have become more common (Cullen et al., 2013a; Jimenez et al., 2022; Levy et al., 2009). The use of tyres that break in case of collision could have reduced the rate of injuries on that obstacle.

Table 2 Obstacles that owners have perceived to be associated with the injury. Number of injuries and percentage of all injuries are presented.

Shaded cells indicate obstacles with at least 10% of all injuries. Cell is blank if the number of injuries on that obstacle was not reported. N is presented as total number of injuries in each study. [a] Estimated from a figure. [b] First-reported injuries for which severity was reported. [c] Obstacle no longer used in agility. Removed due to safety concerns.

Obstacle	Levy et al. 2009 (n=529) [a]	Cullen et al. 2013 (n=1 015) [b]	Kerr et al. 2014 (n=38)	Jimenez et al. 2022 (n=168)
Bar jump	59 (11%)	181 (18%)		34 (20%)
A-frame	98 (19%)	157 (15%)	4 (11%)	12 (7%)
Dogwalk	64 (12%)	120 (12%)	3 (8%)	8 (5%)
Weaves	29 (5%)	44 (4%)		18 (11%)
Seesaw	23 (4%)	41 (4%)		3 (2%)
Tyre	21 (4%)	63 (6%)	3 (8%)	1 (1%)
Spread jump	10 (2%)	39 (4%)		0 (0%)
Long jump	1 (0%)	7 (1%)		0 (0%)
Wall / Panel jump	1 (0%)	6 (1%)		1 (1%)
Open tunnel	16 (3%)	29 (3%)		16 (10%)
Chute [c]	10 (2%)	21 (2%)	4 (11%)	1 (1%)
Pause table	6 (1%)	14 (1%)		1 (1%)

Slippery surface or loss of footing is perceived as a cause for 5–18% of injuries (Cullen et al., 2013a; Levy et al., 2009). A recent survey reported that owners considered 35% of injuries being definitely surface-related, and an additional 21% of injuries were possibly surface-related (Jimenez et al., 2022). Rubber mat was

associated with the highest number of injuries when controlled for exposure, and injury is considered surface-related in almost 90% of cases (Jimenez et al., 2022). Other reported causes for injury include, for example, human-dog collisions and uneven ground (Cullen et al., 2013a).

2.2.2 Description of injury

Anatomical injury locations have been investigated by survey studies and rely fully on owner reports. Table 3 presents injury locations in the seven largest survey studies. Categorisation of body parts varies among studies; thus, the results are not necessarily directly comparable. Additionally, owners may have a limited ability to correctly localise an injury, especially if the injury was not diagnosed by a veterinarian. Similar trends of the most common injury sites occur in many studies despite the limitations. Back and shoulder injuries are typical for agility dogs across all surveys – each comprising roughly 15–30% of all injuries (Cullen et al., 2013a; Essner et al., 2024; Evanow et al., 2021; Jimenez et al., 2022; Levy et al., 2009; Pechette Markley et al., 2021; Sellon et al., 2023). Additionally, injuries of the iliopsoas muscle, digits and stifle are regularly reported (Cullen et al., 2013a; Essner et al., 2024; Evanow et al., 2021; Jimenez et al., 2022; Levy et al., 2009; Pechette Markley et al., 2021; Sellon et al., 2023).

Muscle strain is the most common injury type (45–53% of all injuries), followed by ligament sprains (16–21%), cuts or scrapes (21%), and contusions (13%) (Cullen et al., 2013a; Kerr, Fields, et al., 2014; Levy et al., 2009). According to Markley et al. (2021), the most common shoulder injuries in agility dogs are biceps tendinopathy, medial shoulder syndrome or instability, and supraspinatus tendinopathy. Injuries to the back include intervertebral disc disease, lumbosacral instability and stenosis, arthritis, and strain (Pechette Markley et al., 2021). Iliopsoas injuries are typically strains (Pechette Markley et al., 2021).

Sellon et al. (2018) investigated traumatic digit injuries in agility dogs, with one third of the injuries perceived as agility related. Most (80%) of the digit injuries occurred in forelimbs (Sellon et al., 2018). One-third of all digit injuries affected the most lateral 5th digit; injuries to dewclaws were the least common (Sellon et al., 2018). Reported digit injuries in agility dogs included sprains, strains, fractures, and torn nails (Sellon et al., 2018).

Table 3 Anatomic distributions of injuries in agility dogs. The studies with the largest number of respondents are shown.

Grey cells indicate anatomical locations with at least 10% of all injuries. Blank cells indicate that the anatomical site was not reported in the study. N is presented as the total number of injuries in each study, except for Sellon et al. (2023), for which n is the number of agility dog handlers, and Essner at al. (2024) where n is the number of injured agility dogs.

[a] Paper and web survey was distributed through an agility magazine from the United States. Respondents' countries not reported. [b] Includes only injuries for which recovery time was available. [c] Of all respondents, 85% were from North America and 13% from Europe. [d] Orthopaedic conditions requiring >1 week time-loss from agility regardless of whether the injury was considered agility-related or not. [e] Of all respondents, 72% were from North America, 21% from Europe and 6% from Oceania. [f] Of all respondents, 91% were from North America and 7% from Europe. [g] Number and percentages of agility dog owners who had had at least one agility dog experiencing injury to that body part. Owners were able to choose multiple options. All injuries, irrespective of their perceived cause, requiring moderating or stopping agility training were reported. [h] All injuries irrespective of their perceived cause were included. [i] Lumbar and thoracic spinal and lumbosacral regions combined. [j] Upper and lower thigh regions combined. [k] Digit and paw injuries combined. [l] Includes nail injures.

Anatomical location	**Levy et al. 2009 (n=529)** United States[a]	**Cullen et al. 2013 (n=1 523)[b]** North America[c]	**Evanow et al. 2021 (n=174)** United States	**Markely et al. 2021 (n=1 958)[d]** North America[e]	**Jimenez et al. 2022 (n=168)** North America[f]	**Sellon et al. 2023 (n=1 322)[g]** United States	**Essner et al. 2024 (n=274)[h]** Sweden
Back	99 (18%)	282 (19%)	31 (18%)	594 (30%) [i]	10 (6%)	331 (25%)	43 (16%) [i]
Loin / lumbar spine / lumbosacral		141 (9%)		336 (17%)			
Ribcage or side		50 (3%)		55 (3%)			0 (0%)
Neck		189 (12%)		199 (10%)	5 (3%)	166 (13%)	3 (1%)
Head / snout		72 (5%)		39 (2%)			9 (3%)
Forelimb			41 (24%)		107 (64%)		
Shoulder	107 (20%)	349 (23%)	29 (17%)	589 (30%)	52 (31%)	366 (28%)	20 (7%)
Elbow / brachium		177 (12%)		90 (5%)	1 (1%)	53 (4%)	5 (2%)
Antebrachium		81 (5%)		41 (2%)			
Carpus	(6%)	109 (7%)		166 (8%)	14 (8%)	160 (12%)	6 (2%)

Anatomical location	Levy et al. 2009 (n=529) United States[a]	Cullen et al. 2013 (n=1 523)[b] North America[c]	Evanow et al. 2021 (n=174) United States	Markely et al. 2021 (n=1 958)[d] North America[e]	Jimenez et al. 2022 (n=168) North America[f]	Sellon et al. 2023 (n=1 322)[g] United States	Essner et al. 2024 (n=274)[h] Sweden
Hindlimb			58 (33%)				
M. iliopsoas / flank / croup / groin		105 (7%)	23 (13%)	380 (19%)	21 (13%)	328 (25%)	7 (3%)
Hip	(6%)			169 (9%)	6 (4%)	80 (6%)	8 (3%)
Thigh		265 (17%)[j]		116 (6%)			5 (2%)
Stifle	(12%)	169 (11%)	14 (8%)	261 (13%)	10 (6%)	245 (19%)	29 (11%)
Tibia / fibula				34 (2%)			0 (0%)
Tarsus / calcaneal tendon				34 (2%)	7 (4%)	45 (3%)	8 (3%)
Distal limb							
Metacarpus or metatarsus		66 (4%)		86 (4%)			
Paw pads		48 (3%)		200 (10%)			13 (5%)
Digits	(6%)	202 (13%)	21 (12%)	350 (18%)	25 (15%)	266 (20%)[k]	71 (26%)[l]

2.2.3 Treatment of injuries and return to sport

Veterinary care is sought for 61–78% of agility-related injuries (Cullen et al., 2013a; Levy et al., 2009). Surgical treatment is required for 4–5% of injuries (Cullen et al., 2013a; Kerr, Fields, et al., 2014). Other reported treatments include chiropractic care (43% of injuries), physiotherapy (26%), acupuncture (18%) and massage (6%) (Cullen et al., 2013a). Injuries often take weeks to resolve and may result in retirement from the sport (Table 4). The decision to retire a dog from agility is most commonly due to problems related to the dog's advancing age (30% of agility dog owners), lameness (15%), behavioural or stress-related issues (11%), medical issues unrelated to the sport (10%) and neck or back problems (9%) (Sellon et al., 2023).

Table 4 Severity of agility-related injuries. Severity is defined by the time from injury to recovery. Definitions and reported variables vary between studies. Cell is left blank if the value for it is not reported.

N is presented as total number of injuries in each study. [a] Number of injuries for which time-loss was reported.

Severity	Levy et al. 2009 (n=483) [a]	Cullen et al. 2013 (n=1 602)	Jimenez et al. 2022 (n=168)
Minor	≤6 weeks: 39%	<1 month: 51%	
Severe or chronic	>6 weeks: 49%	≥2 months: 45%	
Unclassified		5%	
Retirement	12%		6%

2.2.4 Risk factors for injury in agility dogs

2.2.4.1 Risk factor analyses

Multiple retrospective survey studies have investigated risk factors for injuries in agility dogs using multivariate regression models (Cullen et al., 2013b; Evanow et al., 2021; Fry et al., 2022; Kerr, Fields, et al., 2014; Kieves et al., 2024; Pechette Markley et al., 2022; Sellon et al., 2018; Sellon & Marcellin-Little, 2022; Sundby et al., 2022). The evaluated dependent variable has been either any injury or orthopaedic condition or injury to a specific body part. Some studies have included only injuries that owners considered to have resulted from agility (Cullen et al., 2013b; Evanow et al., 2021; Kerr, Fields, et al., 2014); others have evaluated risk factors for injuries in agility dog populations irrespective of the perceived cause of injury (Fry et al., 2022; Kieves et al., 2024; Pechette Markley et al., 2022; Sellon et al., 2018; Sellon & Marcellin-Little, 2022; Sundby et al., 2022).

Each factor is first evaluated alone in a univariate model or in an age-adjusted model controlling for the longer lifetime exposure (Cullen et al., 2013b; Evanow et al., 2021; Pechette Markley et al., 2022; Sellon et al., 2018; Sundby et al., 2022). Factors that show some association with the injury in the univariate model ($p<0.1$, $p<0.2$ or $p<0.25$) are then chosen for the development of the final, multivariate model (Cullen et al., 2013b; Evanow et al., 2021; Pechette Markley et al., 2022; Sellon et al., 2018; Sundby et al., 2022). Multivariate models can be constructed in different ways, such as the stepwise backward selection (Evanow et al., 2021; Pechette Markley et al., 2022; Sellon et al., 2018; Sundby et al., 2022). The models aim to find factors that best predict a dependent variable in the studied sample. All factors in multivariate models are adjusted for the effects of other factors in the same model (Huberty & Petoskey, 2000).

The effect of each factor is represented as an odds ratio (OR). Regression models reveal factors that are more common among injured dogs (risk factors, $OR>1$) or among uninjured dogs (protective factors, $OR<1$). One should additionally evaluate the 95% confidence interval (CI) for the OR: if the CI ranges on both sides of 1, the factor cannot be interpreted with certainty due to a non-significant result ($p\geq0.05$).

These analyses do not prove a causal relationship between the factors and injury when using retrospective survey data. Additionally, routines and practices at the time of survey participation may have differed from those before the injury. Reverse causality may explain some findings: instead of certain training-related factors causing injury, it may have been that an injury led to changes in the training routines. Alternatively, the injury and the proposed risk factor may share a common underlying, unknown confounding factor that affects both the injury and risk factor, influencing their association (Howards, 2018). The results can be inaccurate when these confounding factors are not accounted for (Howards, 2018). Thus, the proposed risk and protective factors should be interpreted with caution. The current studies on risk factors offer an important base for future research: prospective studies and experimental research would offer more tools to investigate causality.

Additional limitations in the current studies include the dog handler's ability to identify an injury and difficulties in remembering details of past injuries (recall bias). Risk factors are also likely to differ across different specific injuries, or there may be multiple reasons for a similar injury (e.g., acute trauma and overuse). It is likely to identify risk factors that are shared by the common injuries if a broad range of injuries is included. However, risk factors that are specific to certain injuries are missed.

2.2.4.2 Dog- and handler-related risk factors

Compared to other dog breeds, Border Collies have increased risk for agility-related injuries, orthopaedic conditions in general, stifle injuries, iliopsoas injuries and traumatic digit injuries (Cullen et al., 2013b; Evanow et al., 2021; Fry et al., 2022; Kieves et al., 2024; Sellon et al., 2018; Sundby et al., 2022). Only the risk for cranial cruciate ligament rupture (CCLR) is decreased in Border Collies compared to non-Border Collie agility dogs (Sellon & Marcellin-Little, 2022). Reasons for the high injury risk could include Border Collies having a genetic predisposition for conditions (e.g., shoulder issues) common in agility dogs for non-agility related reasons, predisposing conformation, personality traits, or high speed during agility performance. Border Collies are known to be faster than many other breeds (Alcock et al., 2015; Ketola, 2019). Speed has previously not been evaluated as a risk factor for injuries in agility dogs, but in flyball, faster dogs are at an increased risk of injury (Blake et al., 2023; Pinto et al., 2021). Border Collies may also be owned by handlers whose training or competition practices differ from handlers of other breeds.

Older dogs have been more likely to have suffered an injury in multiple studies (Evanow et al., 2021; Fry et al., 2022; Pechette Markley et al., 2022). This is likely the result of longer exposure time, because injuries have been recorded for the dogs' whole lifetime until the survey participation. Heavier dogs, when controlled for height, had an increased odds of injury in one study (Sundby et al., 2022). Risk of traumatic digit injuries has been reported to increase with higher weight-to-height ratio, long nails, and removal of front dew claws (Sellon et al., 2018).

Results regarding the effect of a dog's and handler's agility experience are conflicting. In an older study, inexperience of both the handler and the dog increased the dog's injury risk (Cullen et al., 2013b). However, factors suggesting high competitiveness have increased risk in more recent studies. These factors include a higher competition level of the dog, multiple participations in national events for the dog, the handler having competed at the national level, the greater number of agility dogs a handler has had, agility as the main sport focus, and a dog acquired with agility in mind (Evanow et al., 2021; Pechette Markley et al., 2022; Sellon et al., 2018; Sellon & Marcellin-Little, 2022; Sundby et al., 2022). Competitiveness may be associated with injury-prone training or competition routines, or the type of dogs used may be more prone to injuries due to their speed, conformation, personality, or other factors. Some of these findings come from models adjusted for breed (Evanow et al., 2021; Sellon et al., 2018; Sundby et al., 2022). In a couple models breed has not been included, and the findings may result from Border Collies being possibly overrepresented among the competitive categories (Pechette Markley et al., 2022; Sellon & Marcellin-Little, 2022).

2.2.4.3 Risk factors relating to training or competition routines

The evaluated training- and competition-related factors vary markedly between studies. Additionally, these agility-related routines may vary over time. The routines around the time of survey participation have usually been asked (Cullen et al., 2013b; Evanow et al., 2021; Pechette Markley et al., 2022), possibly differing from those prior to the injury. Perhaps for this reason, training frequency or duration have not been associated with injury risk (Cullen et al., 2013b; Evanow et al., 2021).

One study reported that starting jump training at a young age (<18 months) increased the injury risk, as did competing at bar heights 5–10 cm above a dog's wither height compared to jumping 0–5 cm below its wither height (Pechette Markley et al., 2022). Some of the additionally reported risk factors, each in one study, include certain weave training methods, frequently competing on dirt or turf (for iliopsoas injuries), and participation in both flyball and agility (for CCLR) (Fry et al., 2022; Pechette Markley et al., 2022; Sellon & Marcellin-Little, 2022). Reported protective factors include starting weave and seesaw training at a young age, frequently competing on rubber mat, participation in other sport activities (excluding flyball, for CCLR) and weekly core strength, balance, stretching, and body awareness exercises (for CCLR) (Pechette Markley et al., 2022; Sellon & Marcellin-Little, 2022).

2.2.5 Towards injury prevention

Injuries cause pain and often restrict normal daily activities, even in the long-term in the worst cases. Thus, reduction of injury rate and injury severity would improve these canine athletes' welfare. Agility dog handlers have highlighted the need for injury prevention by prioritising the following research areas (Sellon et al., 2023):

1. Identifying risk factors for specific types of injuries
2. Improvements in equipment and understanding safe course design
3. Physical conditioning programs to prevent injury
4. Enhancing and prolonging athletic lifespan for dogs

Finch (2006) has described a framework for sport injury prevention in human athletes: Translating Research into Injury Prevention Practice (TRIPP). TRIPP is the extended version of an initial 4-step model from van Mechelen et al. (1992) and considers additionally the implementation of injury prevention protocols into real work practices (Finch, 2006; van Mechelen et al., 1992). The stages of TRIPP are (Finch, 2006):

1) **Injury surveillance.** Evaluation of injury incidence over time and across regions or sports. Standardised definitions for injury and exposure are needed.

2) **Establishing aetiology and mechanism of injury.** A multidisciplinary approach is required to understand injury mechanisms and risk factors for injury. Examples include biomechanical, epidemiological, and clinical studies. Prospective cohort studies are preferred for identification of risk and protective factors, but retrospective case-control studies are more common although limited in power.
3) **Develop preventive measures.** Preventive measures should be suggested based on findings from stages 1 and 2 as well as multidisciplinary knowledge of biomechanics, sport medicine, psychology, etc.
4) **Scientific evaluation of preventive measures.** Intervention efficacy is evaluated in ideal conditions. This stage may include testing on small groups or in a clinical setting. Randomised, controlled field-based studies, the ideal evaluation method, are also considered an artificial environment because the same resources are unavailable outside study participation. Compliance with the intervention should be recorded.
5) **Describe intervention context to inform implementation strategies.** Understanding of the real-world context is required to implement the preventive measures. Information on attitudes, perceptions, and motivations of players, coaches, and other sports bodies as well as resources available for safety improvement should be considered. It is important to understand by whom and under what circumstances the preventive measures should be implemented.
6) **Evaluate effectiveness of preventive measures in the implementation context.** The preventive measures are implemented in the real-world context in the final stage.

This framework could be used to develop injury prevention strategies in canine athletes. Current research in dog agility mainly involves stage 1, which covers the incidence and severity of injuries. However, standardised injury definitions are lacking, and exposure time has not been generally recorded; thus, injury rates (e.g., injury / 1000 exposure hours) are largely unknown. Inertial measurement units (IMUs) could provide a tool to objectively measure exposure in agility dogs, because they can reasonably discriminate agility activity at least from trot and other less intense behaviours (Vitt et al., 2023).

The previously mentioned risk factor studies have additionally started to shed light on the risk factors of stage 2 (Cullen et al., 2013b; Evanow et al., 2021; Pechette Markley et al., 2022; Sellon et al., 2018). Nevertheless, the found risk factors vary vastly, and the causal relationship to injuries is unclear. So far, no prospective cohort studies have been carried out in agility dogs. Some aspects of agility performance have been evaluated in biomechanical studies (e.g., Birch & Leśniak, 2013; Cullen et al., 2017; Pfau et al., 2011; Söhnel et al., 2020).

Further information is required from both stages 1 and 2. The effect of preventative measures has not yet been investigated in agility dogs. A couple of studies have additionally reported concerns or beliefs of sporting dog owners (Essner, Kjellerstedt, et al., 2022; Sellon et al., 2023), which might prove valuable in stage 5.

2.2.5.1 Prevention of overuse injuries

The three most common shoulder conditions in agility dogs – biceps and supraspinatus tendinopathies and medial shoulder syndrome/instability – are thought to result from repetitive microtrauma (Marcellin-Little et al., 2007; Pechette Markley et al., 2021). Additionally, iliopsoas injuries, also common in agility dogs, may result from repetitive microtrauma (Kieves, 2020; Pechette Markley et al., 2021). These are examples of overuse injuries in agility dogs.

Overuse injuries, by definition, result from repetitive microtrauma and do not have a single identifiable incident causing the injury (Fuller et al., 2006). The tissue will be damaged if a mechanical load exceeds the tissues' capacity to withstand the load. A single high-magnitude load can result in an acute injury (Kalkhoven et al., 2020). Damage from lower-magnitude loads (microtrauma) can lead to adaptation with adequate rest and repair, but tissue failure can follow if damage accumulates over time (Edwards, 2018). The increase in risk for overuse injury is more rapid with increasing loading magnitude than with loading cycles (repetitions) when evaluating overuse injuries through the mechanical fatigue phenomenon (Edwards, 2018). Thus, development of overuse injuries can be better understood if we have knowledge on the magnitude of these loads. Development of overuse injuries is not dependent on loads alone; various factors can affect the load tolerance, recovery from microtrauma and the physical attributes that contribute to tissue loading (Kalkhoven et al., 2020).

Research on the biomechanics of agility performance sheds light on these mechanical loads associated with the sport, providing information for stage 2 of the TRIPP framework. Repetitive actions of the sport should be considered when exploring the injury mechanism of overuse injuries. Jumping is a highly prevalent action in the sport: Of a 20-obstacle course, 13 obstacles are generally bar jumps with some additional jumping obstacles (tyre, wall, or long jump) often included (Cullen et al., 2013a). Mechanical loads associated with jumping could play a role in the development of the previously-mentioned injuries.

2.3 Biomechanics of jumping in agility

Biomechanics is the study of biological systems using principles of mechanical engineering. Biomechanical studies aid in estimating the loads the tissues are under

during different sport-related tasks. Additionally, biomechanics can be used to evaluate what factors modify these loads and which could be used to develop course planning, sport regulations or training practices.

2.3.1 Biomechanical measurements

Kinetics and kinematics are fields of biomechanics that are commonly used in canine biomechanical research (Torres, 2020). Kinetics is the study of forces affecting a body and of their effect on motion (Torres, 2020). Kinematics is focused on describing motion with no regard to the forces causing the motion (Torres, 2020).

Ground reaction forces (GRFs) are commonly measured in kinetics. GRF is the force exerted on a body when it is in contact with the ground, and based on Newton's third law, the body is exerting an equal and opposite force on the ground. GRFs are commonly measured using force plates that measure force in three orthogonal axes. A force plate is the gold standard for measurement of lame animals (Torres, 2020). Pressure-sensitive walkways are an alternative method for force estimation that measure pressure instead of force and allow for calculation of vertical force. Both force plates and pressure-sensitive walkways have been used to study biomechanics in agility dogs (Pfau et al., 2011; Pogue et al., 2022; Söhnel et al., 2017, 2021). Commonly reported variables include peak forces and impulses (vertical, accelerative, decelerative). Medio-lateral forces are seldom reported but are important if other than a straight-line movement, such as a turning jump, is studied (Söhnel et al., 2021).

Measured variables in kinematic studies of agility dogs have included, for example, velocity, joint angles, limb length and landing angle (Birch & Leśniak, 2013; Pfau et al., 2011; Söhnel et al., 2020). Certain body parts are tracked to obtain this information by either two-dimensional (2D) systems consisting of one video camera positioned perpendicular to the direction of movement or by three-dimensional (3D) systems consisting of multiple cameras and specialised software (Sandberg et al., 2020). Only one plane of movement can be evaluated with 2D systems, and error will be caused if the camera is not perpendicular to that plane (Sandberg et al., 2023). All three planes of movement can be tracked with a 3D system: sagittal, frontal, and transverse (Sandberg et al., 2020).

Markers are placed on predetermined anatomical landmarks, although in some studies joint locations have been estimated from a video without markers (Alcock et al., 2015; Birch et al., 2015a, 2015b, 2016). The pattern of these markers is called a kinematic model, and the model determines which joint angles can be measured (Sandberg et al., 2020). Only planar 2D kinematic models can be used with 2D systems - studying generally only the sagittal plane (extension – flexion) (Sandberg et al., 2020). Movement in transverse and frontal planes could also be evaluated

with 3D systems but require markedly larger numbers of markers to be used for each joint (Sandberg et al., 2020). 2D models are applied in most canine kinematic studies even when using 3D system for marker tracking (Sandberg et al., 2020; Torres, 2020). The results of 2D and 3D models are comparable when evaluating joint extension and flexion, at least after waveform alignment (Sandberg et al., 2023; Torres et al., 2010). Shoulder and elbow absolute angles may be larger than with more complex models with the most simple, linear 2D model, but the shape of the waveform and amplitude is similar (Sandberg et al., 2023).

Commonly reported joint kinematics values include minimum (peak flexion) and maximum (peak extension) values as well as range of motion (ROM) during the stride cycle (Torres, 2020). However, joint angles have been evaluated in most agility studies only at certain time points (e.g., just before lift-off) instead of continuously recording (Birch et al., 2015a, 2015b, 2016; Birch & Leśniak, 2013). Regardless of system or model, marker movement over the anatomical landmarks due to skin displacement produces error, and joint angle values are always only estimates of the actual movement in the joint (Fischer et al., 2018; Kim et al., 2011; Schwencke et al., 2012). This soft tissue artefact is larger in more proximal joints (Fischer et al., 2018). Fluoroscopy, radiographic video, can be used to overcome the issue (Fischer et al., 2018).

Some biomechanical evaluations require both kinetic and kinematic data: for example, limb stiffness has been calculated in agility dogs using limb length and ground reaction force measurements (Söhnel et al., 2020). A stiff limb resists the shortening of the limb length (limb compression) against ground reaction forces along its axis (Söhnel et al., 2020). Other examples include inverse dynamics in which net torque at each joint can be calculated using kinematic and kinetic data as well as the known inertial properties of different limb segments (Whittlesey & Robertson, 2014). So far, inverse dynamics have not been studied in agility dogs.

None of the just-mentioned methods directly measure loads, such as strain or stress, on specific injury-prone tissues. Direct measurement of these loads, especially non-invasively, is very challenging in living animals (Q. Zhang et al., 2021). Therefore, simulated computer models have been created in humans to estimate ligament strain or muscle force (Erdemir et al., 2007; Y. Zhang et al., 2011). Loads on the anterior cruciate ligament and cervical spine tissues in canines have been estimated using computer modelling (Alizadeh et al., 2017; Brown et al., 2014, 2015a, 2015b). Additionally, muscle forces in the hind limb have been estimated in walking (Shahar & Banks-Sills, 2002). A full-body musculoskeletal model of a dog has been created (Stark et al., 2021, 2022) but, to my knowledge, has not yet been used to study orthopaedic conditions or sport performances. Another type of modelling has been described in a non-peer-reviewed article studying the aerial phase of jumping in agility dogs: the multisegmented model was

created to evaluate the impact of different body parts on the rotational inertia of the dog (Rottier et al., 2023).

2.3.2 Jumping in agility dogs

Multiple studies have researched the biomechanics of jumping in agility and various aspects affecting it (e.g. Birch et al., 2015a; Birch & Leśniak, 2013; Pfau et al., 2011; Söhnel et al., 2020, 2021). Jumping is a highly prevalent action in agility, and loads associated with jumping may be contributing to the development of injuries. The key difference between running and jumping is the need to rapidly increase vertical velocity at take-off to raise the body above the obstacle height. Dogs approach and leave obstacles at speed in agility, requiring the ability to quickly transfer the mainly horizontal movement into a more vertical direction at take-off and the opposite at landing.

Table 5 presents a comparison to a high-speed gallop for selected stride parameters and kinetic variables to evaluate jumping's physical demands. Both jumping in agility and gallop are asymmetrical movement patterns in which the loads are different for the trailing limb that contacts the ground first and the leading limb that follows (Söhnel et al., 2020; Walter & Carrier, 2007). Considering studies on jumping and galloping, an important note should be made on the differences in velocity, which are known to affect the biomechanics (Hudson et al., 2012; Torres, 2020). A greater velocity is associated with increased peak vertical forces (PVFs) during jumping, along with a decreased stance time in all four limbs during take-off and landing (Söhnel et al., 2020). Equally in gallop, stance times are shorter at a higher velocity (Hudson et al., 2012). Vertical and accelerative impulses in the hindlimbs are lower when jumping at a higher velocity (Söhnel et al., 2020). However, peak vertical forces and accelerative impulses increase in the hindlimbs in gallop, whereas vertical impulses decrease in the forelimbs with increasing velocity – indicating a shift of weight to the hindlimbs at greater speeds (Hudson et al., 2012). An additional limitation for a straightforward comparison of the studies of jumping and galloping is the variation in breeds: gallop studies are mainly done on greyhounds, whereas the listed agility studies have included Border Collies (Hudson et al., 2012; Pfau et al., 2011; Pogue et al., 2022; Söhnel et al., 2020; Walter & Carrier, 2007). Thus, some of the differences in Table 5 may be due to breed differences instead of actual differences between gallop and jumping.

Speed of agility dogs when performing straight-line, multi-obstacle jumping sequences has ranged from 4 to 9 m/s with even greater speeds at a very low bar height (<50% of wither height) (Alcock et al., 2015; Birch et al., 2015a, 2015b, 2016; Pfau et al., 2011; Söhnel et al., 2020). In addition to bar height, speed is affected by the distance between obstacles, the dog's experience, size and breed as well as being

correlated with jumping style (Alcock et al., 2015; Birch et al., 2015b, 2015a, 2016; Pfau et al., 2011; Söhnel et al., 2020).

Table 5 Stride parameters and kinetics during take-off to and landing from a straight-line bar jump in agility dogs as well as during straight-line high-speed gallop.

[a] Söhnel et al. (2020): mean velocity 4.7–6.3 m/s. [b] Pogue et al (2022): mean velocity at approach 0.9 m/s. As a difference from other studies, forces were measured with a pressure-sensitive walkway, not with force plates. [c] Pfau et al. (2011): mean velocity 7.9 m/s for jump landing and 9.6 m/s for gallop, impulse values were estimated from a figure. [d] Walter & Carrier (2006): mean velocity 9.2 m/s. [e] Hudson et al. (2012): velocity 9.9-19.0 m/s for weight distribution and 8–12 m/s for other values. Synchronicity and peak force estimated from a figure.

	Jump take-off	**Jump landing**	**Gallop**
Stance time (ms)			
Trailing forelimb	104–118 [a]	87–102 [a]	71 [d]
Leading forelimb	94–100 [a]	100–123 [a]	75 [d]
Trailing hindlimb	91–98 [a]	88–106 [a]	74 [d]
Leading hindlimb	86–95 [a]	89–115 [a]	72 [d]
Temporal synchronicity (% of trailing limb stance time)			
Forelimbs	42–57 [a]	33–37 [a]	78 [e]
Hindlimbs	14–17 [a]	43–46 [a]	89 [e]
Peak vertical force (BW)			
Trailing forelimb	2.1–2.2 [a]	2.3–2.8 [a,b]	2.2–2.3 [d,e]
Leading forelimb	1.8–1.9 [a]	2.1–2.5 [a,b]	2.1–2.3 [d,e]
Trailing hindlimb	1.6–1.7 [a]	1.3–1.4 [a]	1.5–1.7 [d,e]
Leading hindlimb	1.70 [a]	1.1–1.3 [a]	1.6 [d,e]
Vertical impulse (BWms)			
Trailing forelimb	128–141 [a]	131–138 [a]	92 [d]
Leading forelimb	102–106 [a]	150–153 [a]	92 [d]
Forelimbs combined	230–247 [a]	260–291 [a,c]	184-190 [c,d]
Trailing hindlimb	97–99 [a]	75–76 [a]	69 [d]
Leading hindlimb	93–97 [a]	69–74 [a]	70 [d]
Hindlimbs combined	190–196 [a]	144–175 [a,c]	139-140 [c,d]
Weight distribution (% of total vertical impulse on forelimbs)	55–56 [a]	60–66 [a,c]	57–58 [c,d,e]
Net cranio-caudal impulse (BWms)			
Forelimbs combined	-29–(-26) [a]	-29–(-6) [a], 46 [c]	2 [c,d]
Hindlimbs combined	0–7 [a]	-13–9 [a], 50 [c]	4–14 [c,d]

2.3.2.1 Take-off to a straight-line jump

This study defines take-off to jump as the last ground contact of each limb before the aerial phase. The reported mean take-off distances, the distance between the hindlimbs and the obstacle, to a straight-line jump vary from 0.80 m to 1.95 m in intermediate and large category dogs (Birch et al., 2015b; Miró et al., 2020; Söhnel et al., 2020). Advanced dogs competing at higher levels typically take off farther away from the obstacle than beginner dogs (Birch et al., 2015b; Söhnel et al., 2020). Take-off distance is additionally affected by the distance between jumps (Birch et al., 2015b).

Forelimbs contact the ground asynchronously at take-off (Söhnel et al., 2020). However, the duration between touchdowns of trailing and leading forelimbs appears much longer in gallop than during jump take-off, meaning that the forelimbs are more synchronous during take-off than during high-speed gallop (Table 8) (Hudson et al., 2012; Söhnel et al., 2020). The leading forelimb (2nd on ground) touches the ground approximately 25 to 35 cm in front of the trailing forelimb (1st on ground) in Border Collies (Söhnel et al., 2021). The jumping biomechanics of beginner dogs, competing in the lowest classes with less than four years of experience in the sport, have been compared to advanced dogs that competed in the highest class and had over four years of experience in the sport (Söhnel et al., 2020). Forelimb placement is less synchronous and wider apart in beginner dogs than in advanced dogs (Söhnel et al., 2020). Thus, forelimb coordination of beginner dogs resembles more that of a gallop than in advanced dogs. The beginner dogs may lack the ability to increase synchronicity of the forelimbs when approaching at gallop.

The leading forelimb is 75% stiffer than the trailing forelimb with less compression of the limb, indicating a strut-like action (Söhnel et al., 2020). This may allow dogs to transfer the horizontal motion at take-off into vertical velocity. The PVF and vertical impulse are higher in the trailing forelimb than in the leading forelimb. The decelerative impulses in both forelimbs are greater than the accelerative impulse, resulting in deceleration of the horizontal velocity during the forelimb stance (Söhnel et al., 2020). This differs from the steady-state gallop, where this net cranio-caudal impulse in the forelimbs is around zero (Walter & Carrier, 2007). The forelimb muscles, such as *m. biceps brachii*, *m. supraspinatus* and *m. triceps brachii*, are highly activated during jumping in agility with one of the peak activations occurring during take-off (Cullen et al., 2017).

At take-off, the hindlimbs contact the ground almost simultaneously and parallel to each other with much greater synchronicity than what is reported in galloping dogs (Hudson et al., 2012; Söhnel et al., 2020). The forces produced by the trailing and leading hindlimbs are similar except that the trailing hindlimb has a greater role in acceleration (Söhnel et al., 2020). The net cranio-caudal impulse produced by the hindlimbs is accelerative in experienced agility dogs, as in gallop

(Söhnel et al., 2020; Walter & Carrier, 2007). However, the net impulse is around zero in beginner dogs due to lower accelerative and greater decelerative impulses, suggesting that advanced dogs are more capable of jumping at speed (Söhnel et al., 2020).

The weight distribution, meaning distribution of produced vertical impulse on fore- and hindlimbs, is similar at take-off and in gallop (Hudson et al., 2012; Pfau et al., 2011; Walter & Carrier, 2007). However, vertical impulse values appear to be greater for all limbs during jump take-off compared to gallop on the flat (Söhnel et al., 2020; Walter & Carrier, 2007). These findings suggest that all four limbs contribute to increase the vertical velocity during take-off.

Joint kinematics at take-off are sparsely studied. The greater compression of trailing forelimb, compared to leading forelimbs (Söhnel et al., 2020), is the result of greater joint flexion in the shoulder and/or elbow and/or extension of the carpal joint. Sagittal joint angles have been evaluated only from still frames from two time points of take-off: early take-off just before fore-limbs lift-off and late take-off just before hindlimbs lift-off (Birch et al., 2016; Birch & Leśniak, 2013). Tarsal joint and lumbar spine are more extended at late take-off and elbow and shoulder more flexed at high bar height (151% of wither height) compared to lower bar height (93% of wither height) in a small sample of mainly large gundog breeds competing in agility (Birch & Leśniak, 2013). However, these results were not reproduced in a larger sample of Border Collies (Birch et al., 2016). Extension of the lumbar spine at late take-off is greater with obstacle spacing that produces a short take-off distance (Birch et al., 2015).

2.3.2.2 Aerial phase over a straight-line jump

The take-off is followed by an aerial phase over the jump, where none of the dog's limbs are in contact with ground or the obstacle. The dog's centre of gravity during this time travels in the direction directed by the take-off. Gravity and possibly some aerial resistance are the only forces acting on the centre of gravity in the air. Thus, the dog cannot affect the trajectory of its centre of gravity during the aerial phase. The reported length of the jump trajectory for competition bar heights ranges from approximately 2.5 m to 3.5 m in intermediate and large category dogs (Birch et al., 2016; Miró et al., 2020; Söhnel et al., 2020). The trajectory appears to be longer in more advanced dogs and more skilled jumpers, as well as at higher velocities (Miró et al., 2020; Söhnel et al., 2020). Additionally, the length increases with bar height until the bar height is 125% of dogs' wither height whereafter it starts to decrease (Birch et al., 2016).

With increasing bar height, greater flexion of shoulder and elbow joints is observed, which is reflected in peak activations of muscles flexing and stabilising these joints during this phase of the jump (Birch et al., 2016; Birch & Leśniak, 2013;

Cullen et al., 2017). So far, breed differences in jumping style have been evaluated only during the aerial phase: the topline angle differs between collie breeds and non-collie breeds in elite agility dogs (Alcock et al., 2015).

The shape of trajectory and its relation to obstacle position has been evaluated in a small group of dogs, categorised into excellent and less-skilled jumpers by expert agility trainers (Miró et al., 2020). In less-skilled jumpers, a higher proportion of the aerial phase (both in duration and distance) was before the obstacle than in excellent jumpers (Miró et al., 2020). The line of back was close to horizontal when the dog was above the obstacle in excellent jumpers but angled downwards (nose-down) in less-skilled jumpers (Miró et al., 2020).

2.3.2.3 Landing from a straight-line jump

Dogs approach the ground at an angle with velocity both downwards and forwards. This motion is redirected into a mainly horizontal direction at landing. The landing angle from a bar jump (60 cm) is steeper than from a long jump, which had a maximum height of 38 cm and length of 1.5 m (Pfau et al., 2011). The steeper landing angel correlated with increased PVF, vertical impulse and accelerative impulse in both fore- and hindlimbs in the same study. The reported mean landing distance varies from approximately 1 m to 1.6 m in intermediate and large category dogs (Birch et al., 2015b; Miró et al., 2020; Söhnel et al., 2020). Landing distance is affected by spacing between obstacles and a dog's competition level (Birch et al., 2015b, 2015a).

Like at take-off, the forelimbs do not contact the ground simultaneously at touch-down (Söhnel et al., 2020). However, the touchdowns of forelimbs are temporally more synchronous than at take-off (Söhnel et al., 2020). Opposite to take-off, the trailing forelimb is stiffer (14%) than the leading forelimb with greater compression in the leading forelimb (Söhnel et al., 2020). Thus, the strut-like action is also present in landing, although less pronounced than at take-off, but the roles of the trailing and leading forelimb are reversed (Söhnel et al., 2020). The forelimb closer to the obstacle is the stiffer one in take-off and landing (Söhnel et al., 2020).

The PVFs of the forelimbs are greater at landing than at take-off (Söhnel et al., 2020). Peak values reach roughly 2.5 times the dog's body weight with no difference between the two below-withers bar heights at a controlled speed (Pogue et al., 2022; Söhnel et al., 2021). These peak forces could result in significant torques around joints that dogs would need to resist at landing. Beginner dogs seem to struggle with these forces: their forelimbs have lower limb stiffness and compress more at landing than the forelimbs of advanced dogs (Söhnel et al., 2020). This may be due to poorer pre-activation of anti-gravity muscles before the ground contact in the beginner dogs (Söhnel et al., 2020). Unexpectedly, two shoulder extensors muscles (*m. supraspinatus* and *m. biceps brachii*), which could have a role in resisting limb

compression as well as in shoulder stabilisation, show the lowest peak activations at landing compared to other phases of jumping (Cullen et al., 2017). Muscle activation of other forelimb muscles has not been studied in dogs landing from a jump obstacle, but landing from a vertical jump where hindlimbs contacted the ground before the forelimbs has been investigated (Tokuriki, 1979). In this impact, *m. supraspinatus* and the anti-gravity muscles *m. infraspinatus* and *m. triceps brachii* were activated just before and during the impact with a magnitude of activation similar to that during jump take-off (Tokuriki, 1979). Further research is required to determine whether forelimb muscle activation differs between advanced and beginner dogs.

Hindlimbs are less synchronous at landing compared to take-off (Söhnel et al., 2020) but not as asynchronous as in a high-speed gallop (Hudson et al., 2012). PVFs in hindlimbs at landing are lower than during take-off (Söhnel et al., 2020). At landing, 60–66% of the total vertical impulse is distributed to the forelimbs (Pfau et al., 2011; Söhnel et al., 2020), which appears to be more than in gallop (57–58%) (Hudson et al., 2012; Pfau et al., 2011; Walter & Carrier, 2007). Net cranio-caudal impulses in the forelimbs were decelerative, whereas hindlimb impulses varied around zero in one study (Söhnel et al., 2020). However, fore- and hindlimbs produced markedly higher accelerative impulses at jump landing with greatly accelerative net cranio-caudal impulses in another study (Pfau et al., 2011), like those reported in dogs during rapid acceleration starting from a standing position (Walter & Carrier, 2009). The study set-ups were relatively similar and the reason for this difference is unknown.

Advanced dogs produce greater accelerative impulse with both fore- and hindlimbs at landing than beginner dogs, resulting in greater velocity (Söhnel et al., 2020). Advanced dogs change earlier in the stance phase from deceleration into acceleration, indicating quicker roll-over, and they additionally have greater limb extension at the end of stance in all limbs, allowing the acceleration to last longer (Söhnel et al., 2020). Additionally, the forelimbs of advanced dogs touch the ground with less synchronicity (Söhnel et al., 2020), which resembles a gallop more than in beginner dogs (Hudson et al., 2012). As a conclusion, beginner dogs appear to have a poorer ability to change from a gallop to the more synchronous take-off stride and to deal with landing impact while transferring to gallop-like striding. Advanced dogs may be further along in learning the motor skill or have better physical capabilities, such as muscle strength.

As with take-off, knowledge of kinematics is sparse. At first ground contact of landing, neck extension, measured from the skull to C2/C3 to the withers, increases with bar height and is greater if the spacing between the bar jumps is tight (below 5 m) (Birch et al., 2015b, 2016). The lumbar spine extension also increases with increases in the bar height (Birch et al., 2016). However, these angles were estimated without markers, and only specific time points were evaluated without

information on the peak angles or the range of motion. The peak extension of the carpus during the stance phase at landing is over 235° in the trailing and leading forelimbs and is not restricted by a flexible neoprene brace (Castilla et al., 2020). These values are higher than the reported values in trotting or galloping dogs (Fischer & Lilje, 2014a), suggesting that landing may cause high stress on the tissues that limit the extension.

2.3.2.4 Turning jump

Almost all studies on jumping evaluate movement in a straight line. However, based on experience in the field, jumps are often approached at an angle. The path may continue with a turn after the jump. So far, a turning jump, with a straight approach but a tight turn at landing, has only been evaluated in three papers, presumably utilising the same data set, with only one of the papers being peer reviewed (Rottier et al., 2023; Söhnel et al., 2017, 2021).

Compared to a straight-line jump, a turning jump seems to have a shorter take-off distance and a slower approach velocity (Söhnel et al., 2020, 2021). The outer forelimb is the trailing one in most dogs, but the inner limb may contact the ground first, especially among beginners (Söhnel et al., 2021). As in a straight-line, the hindlimbs contact the ground almost simultaneously (Söhnel et al., 2020, 2021). The dog's trunk continues to rotate during the aerial phase around the centre of gravity towards the direction of the turn (yaw) and around its axis (roll) because of the torque produced during the take-off (Rottier et al., 2023; Söhnel et al., 2021). Additionally, both in turning and straight-line jumps, a nose-down rotation (pitch) of the trunk occurs during the aerial phase (Rottier et al., 2023). The positions of the body parts relative to the centre of gravity can change the body's resistance to the rotation (rotational inertia), which can slow down or accelerate the rotation. The modelling-based study shows that changes in limb or tail positions during the turning jump have little effect on the inertia, whereas the movement of the back affects the rotation over the jump (Rottier et al., 2023).

Trailing and leading limbs contact the ground almost simultaneously in both pairs of limbs at landing, which differs from straight-line jumping where both pairs of limbs land asynchronously (Söhnel et al., 2020, 2021). The dog uses the inner forelimb as a stable point at landing through positioning it close to the centre of mass and a long stance time (Söhnel et al., 2021). This is enabled by the passive rotation between ulna and radius (Fischer & Lilje, 2014a).

The outer limbs produce higher lateral impulses and peak forces than the inner limbs, thus drive the turning at take-off and landing (Söhnel et al., 2021). Both peak vertical forces and vertical impulses are additionally higher on the outer limb, especially in advanced dogs (Söhnel et al., 2021). Greater vertical forces improve the grip of the outer limbs by increasing the frictional force. Peak vertical forces

(PVFs) appear lower than during straight-line jumps – possibly due to the slower speed (Söhnel et al., 2020, 2021). All limbs show greater deceleration at take-off for a turning jump compared to a straight-line jump with little to no acceleration from the forelimbs (Söhnel et al., 2020, 2021). The net impulse produced by the forelimbs is again decelerative at landing, whereas the net impulse from the hindlimbs is accelerative (Söhnel et al., 2020, 2021). However, the forelimbs produce greater lateral impulses at landing than the hindlimbs, suggesting that the forelimbs play an important role in redirecting the body at landing with the hindlimbs then initiating the acceleration into a new direction (Söhnel et al., 2021).

Differences in forelimb stiffness have not been observed at take-off to turn, although this occurs during straight-line jumping (Söhnel et al., 2020, 2021). Vertical forces are greater on the outer limb, resulting in greater limb compression than in the inner forelimb (Söhnel et al., 2021). The outer limb has greater limb stiffness in the forelimbs at landing as well as for the hindlimbs in both take-off and landing, which leads to similar limb compression in the inner and outer limbs despite the higher vertical forces on the outer limb (Söhnel et al., 2021). Compared to straight-line jumping, the limb stiffness in all limbs appears lower during a turning jump (Söhnel et al., 2020, 2021). Therefore, the limb compression is relatively similar to straight-line jumping despite the lower force magnitudes (Söhnel et al., 2020, 2021). Additionally, when landing from a turning jump, the limb length at toe-off is shorter than at touch-down, resulting in a crouched posture at the end of landing (Söhnel et al., 2021). This position resembles the lowered posture at acceleration initiation, which is an advantage for the production of accelerative forces (Walter & Carrier, 2009).

Advanced dogs produce greater lateral impulses at take-off and landing compared to beginner dogs with both fore- and hindlimbs (Söhnel et al., 2021). Beginner dogs seem to produce a higher percentage of the total lateral impulse by the forelimbs (58%) than advanced dogs (51%) at take-off (Söhnel et al., 2021). Additionally, advanced dogs produce a greater accelerative impulse with the outer than the inner hindlimb and create throughout additional rotation towards the turning direction (Söhnel et al., 2021). These result in greater turning angles and, thus, tighter turning in advanced dogs (Söhnel et al., 2021).

2.3.2.5 Jumping biomechanics and injuries

Information is lacking on the variation of jumping parameters between different breeds and conformations. Landing biomechanics are associated in humans with anterior cruciate ligament injury and some lower extremity overuse injuries (De Bleecker et al., 2020; Hewett et al., 2016). Associations between jumping style and injury have not been evaluated in agility dogs, but individual variation in the jumping style may explain differences in injury risk or competitive performance

because jumping is a highly frequent action in the sport. Among elite agility dogs, collie-breed dogs (likely mainly Border Collies) are faster and bend their heads ventrally when above the obstacle, whereas other non-collie breed dogs lifted theirs up (Alcock et al., 2015). Further research is required to determine whether the jumping style or speed of Border Collies contributes to their increased injury risk.

During jumping, peak forces are of similar magnitude with a straight-line high-speed gallop (Pogue et al., 2022; Söhnel et al., 2020; Walter & Carrier, 2007) and lower-than-estimated peak forces of up to five times a dog's body weight in greyhounds galloping around the curve (Usherwood & Wilson, 2005). Vertical impulses are greater at take-off and landing in all limbs compared to a gallop with even greater differences in moderate activities such as trotting (Pfau et al., 2011; Söhnel et al., 2020; Voss et al., 2011; Walter & Carrier, 2007). It may be that beginner dogs are at higher risk of injuries because they are less capable of resisting these forces at landing, resulting in greater compression of forelimbs compared to advanced dogs – probably leading to high eccentric muscle forces (Söhnel et al., 2020). Greater flexion of the shoulder and/or elbow joints at landing may increase the demands on the soft tissues compared to advanced dogs and potentially lead more rapidly to fatigue, which may predispose to injuries. Lower limb stiffness in humans can be increased with plyometric jump training (Moran et al., 2023), suggesting that physical conditioning could potentially be useful in increasing limb stiffness of beginner dogs. However, high limb stiffness at landing in advanced dogs may increase loads on bone and cartilage.

The greatest peak lateral force, equal to one body weight, is applied on the outer forelimb at landing (Söhnel et al., 2021). The magnitude of abduction or adduction torque at each joint is currently unknown, but these mediolateral forces could contribute to the development of injuries to the structures stabilising the joints. For example, the shoulder joint is stabilised by *m. biceps brachii*, *m. supraspinatus*, *m. subscapularis* and the medial glenohumeral ligament (Kiefer & von Pfeil, 2020), which are commonly injured in agility dogs (Pechette Markley et al., 2021).

Competing at bar heights above a dog's wither height has been associated with increased injury risk in one study (Pechette Markley et al., 2022). Bar height does not appear to affect the peak vertical forces at landing at controlled low speed and below-withers bar heights (Pogue et al., 2022). However, in military working dogs, higher obstacle height increased peak forces at landing (Yanoff et al., 1992). Evaluation of a course-like set up would help to identify the effect of bar height on kinetics in a truly sport-specific setting. Bar height affects speed and length of trajectory in a multi-obstacle sequence (Birch et al., 2016). Thus, various alterations in jumping may affect the loads associated with the bar height in sport-specific situations.

Aims

The overall aim of this research is to improve the understanding of the physical demands placed on agility dogs. The additional aim is to provide insights into the incidence of injuries and propose potential injury mechanisms in these dogs, with injury prevention as the long-term goal. Specific aims are:

1) to investigate sport-related management, training, and competition routines in competition-level agility dogs in Finland (study I)
2) to describe agility-related injuries and their perceived causes as reported by the owners of Finnish agility dogs (study II)
3) to evaluate risk factors for agility-related injuries (study II)
4) to investigate the effect of bar height on jumping biomechanics at take-off to a bar jump (study III)

3 Materials and methods

This research comprised a questionnaire study on routines and injuries of Finnish agility dogs (studies I and II) and a biomechanical study on the effects of three different bar heights on the take-off (study III). Further details on the materials and methods are described in Inkilä et al. (2022a, 2022b, 2024).

3.1 Study population (I-III)

All studies used Finnish client-owned, competition-level agility dogs. Dogs had to have competed in Finland, but the competition class was not defined. Studies I and II evaluated sport routines and injuries in 2019 (previous full year); therefore, only dogs that had trained agility during 2019 and competed in 2018 and/or 2019 were included. Studies I and II included all breeds of dogs.

Study III only included Border Collies to limit variability in biomechanics due to breed. Physical and orthopaedic examinations were conducted prior to measurements by a veterinary orthopaedic surgeon. Dogs were excluded if they were not considered fit to perform based on the examination or if they had suffered injuries within two months prior to participation. Viikki Campus Research Ethics Committee approved the study design (statement 10/2019).

3.2 Questionnaire (I-II)

A retrospective online questionnaire was developed to collect data for studies I and II. The questions covered each dog's signalment, the dog's and its handler's agility experience, and its background health information. The questionnaire contained mainly closed-end multiple-choice questions and was offered only in the Finnish language. The owners were asked whether their dog had suffered an agility-related injury during 2019. Injury was defined as a clinical sign that was observed with 24 hours of performing agility and that required restriction of exercise or sport participation.

Of the non-injured dogs, details on sport routines in 2019 were surveyed. Topics included training frequency and duration, competition practices, warm-up, cool-down, musculoskeletal care (e.g., physiotherapy), exercise and conditioning. The same questions were asked about injured dogs, with the exception that routines

during the three-month period prior to the injury were investigated for most variables. Regarding agility-related injuries during the examined year, questions were asked about the context and a description of the injury as well as its treatment and recovery. Details on the covered variables can be found in Inkilä et al. (2022a and 2022b).

In addition to the questionnaire data, competition results from the Finnish Agility Association's database were used: competition frequency during the three-month period (injured dogs) or whole previous year (non-injured dogs) were retrieved from the database. Additionally, results from two previous full years were used to calculate the mean speed of faultless runs and the percentage of faultless runs for each dog.

3.3 Kinetic and kinematic measurements (III)

Study III evaluated the effect of bar height on canine biomechanics at take-off in a straight-line sequence of three bar jumps. Three jumps were used to gain course-like speed and approach. Take-off to the second in the sequence jump was studied. Take-off was defined as the last ground contact of each limb before the aerial phase. All bar jumps were at the same heights at each trial: either 80%, 100% or 120% of the dogs' wither height, because these represent the variation in bar heights in the sport.

Ground reaction forces were measured with force plates (AMTI Inc, Watertown, MA, USA) placed at the take-off area. Forces were measured for pairs of limbs (e.g., forelimbs) and not for individual limbs due to the size and orientation of the force plates, because trailing and leading limbs contacted the same force plate. Measured kinetic variables included peak vertical force, vertical impulse, decelerative impulse, accelerative impulse and net cranio-caudal impulse calculated separately for forelimbs and hindlimbs. The distribution of total vertical impulse on fore- and hindlimbs (weight distribution) was additionally calculated. The fore- and hindlimbs contacted the same force plate simultaneously in some trials, leading to force curves overlapping with each other. To calculate impulse values from these trials, the lowest vertical force value was used as the cut-off to define which forces were calculated into the forelimb impulse values and which into the hindlimb impulse values as previously performed by Pfau et al. (2011). Further information, along with the investigation into the potential error caused by this approach, can be found in Inkilä et al. (2024).

Reflective markers were attached on anatomical landmarks (Figure 4) and tracked by a 3D motion capture system (Vicon Motion Systems, Oxford, UK) with 15 cameras (Vero v2.2). Using marker and force plate data, touch-down and lift-off of each limb was recorded to define the stance phase. The last stance phase of each limb before the aerial phase was analysed. Sagittal joint angles (flexion – extension)

were measured during the stance phase: peak extension (maximum numerical value) and peak flexion (minimum numerical value) angles and range of motion (ROM) were recorded for each limb. Additional kinematic variables included horizontal velocity, take-off distance, take-off angle, trunk height at the apex of the jump, temporal synchronicity of limbs, distance between limbs and limb angle. A detailed description of the measured kinematic variables can be found in Inkilä et al. (2024). The number of strides between the first and second obstacle was recorded using marker and force plate data.

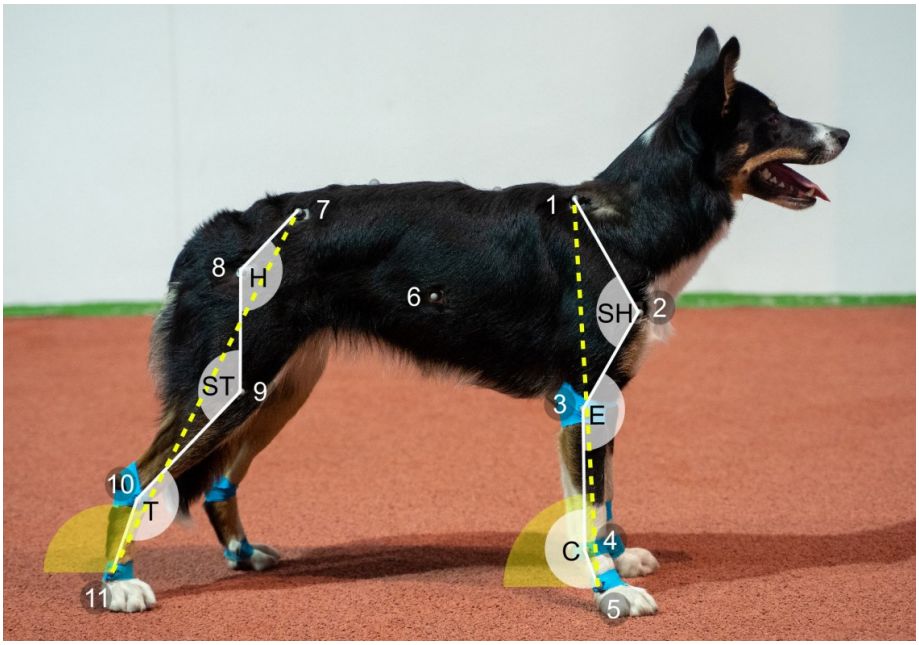


Figure 4 Pattern of reflective markers and measured sagittal joint angles. Joint angles were measured during the stance phase of each limb at take-off. A virtual trunk marker was created between markers on the sides (6) and used to measure the velocity and take-off angle. 1 = dorsal border of scapula, 2 = greater tubercle of humerus, 3 = lateral humeral epicondyle, 4 = ulnar styloid process, 5 = distal end of fifth metacarpal, 6 = over the 11th rib at the level of the shoulder, 7 = cranial dorsal iliac spine, 8 = greater trochanter of femur, 9 = lateral femoral epicondyle, 10 = lateral malleolus of fibula, 11 = distal end of fifth metatarsal. SH = shoulder, E = elbow, C = carpus, H = hip, ST = stifle, T = tarsus. The dashed yellow line marks the line used for limb angle calculation. Figure from Inkilä et al. (2024).

3.4 Statistics

3.4.1 Study I

The median and interquartile range were used for descriptive statistics due to the non-normality of the data. Differences in the training or competition routines and

management between height categories or competition levels were analysed using the Kruskal–Wallis test with Bonferroni corrections for the pairwise comparisons or Pearson's chi-squared test. The effect size of Pearson's chi-squared test is reported with Cramer's V value. Differences between categories were analysed using Z-test with Bonferroni corrections.

Significance was set at $p < 0.05$. Statistical analyses were run in SAS (version 9.4, SAS Institute Inc., Cary, NC, USA) and SPSS (version 26, IBM Corp., Armonk, NY, USA).

3.4.2 Study II

Descriptive statistics included median and interquartile range (IQR) for continuous variables and frequency tables for categorical variables. The association of obstacle collision with obstacle category and/or competition speed of the dog were evaluated with a multivariate binary regression model. Regression was also used to evaluate if a surface or obstacle category was associated with a slipping injury during obstacle performance. Additionally, regression was used to evaluate if surface, surface familiarity or competition speed was associated with a slipping injury.

Each variable was first evaluated with a univariate logistic regression to investigate risk factors for agility-related injury during 2019. The final multivariate model was developed from variables with $p<0.1$ in the univariate regression model by fitting a penalised least absolute shrinkage and selection operator (LASSO) logistic regression model. The criteria for optimal model selection were Akaike information criteria (AIC). Nesteroc optimisation was used as the optimisation technique.

Significance was set at $p < 0.05$. Statistical analyses were conducted in SAS (version 9.4, SAS Institute Inc., Cary, NC, USA) and SPSS (version 26, IBM Corp., Armonk, NY, USA).

3.4.3 Study III

The bar height effect was evaluated with a linear mixed model. Preliminary evaluations suggested an association between stride number (between first and second obstacle) and multiple studied variables, so the stride number was additionally included in the model. The dog was used as a random effect alongside the fixed effects bar height and stride number. Additionally, an association between the stride number and bar height was evaluated with a Chi-squared test.

Significance was set at $p<0.05$. Analyses were conducted in R version 4.2.2 (R Core Team).

4 Results

4.1 Study population

4.1.1 Studies I and II

Survey data were provided by 763 agility dog owners from a total of 864 agility dogs included in studies I and/or II (Figure 5).

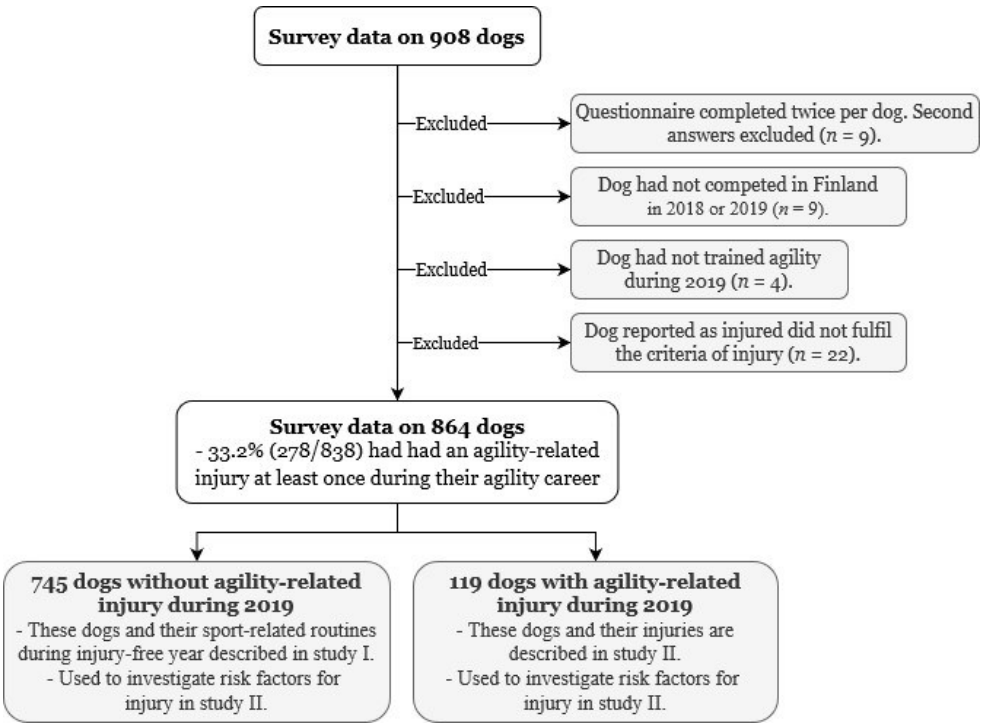


Figure 5 Inclusion of dogs in studies I and II. Figure modified based on Inkilä et al. (2022b).

Table 6 presents the details on the dogs in studies I and II. Handlers had 9 years of agility experience (IQR 5-14 years) at the median. The highest-achieved competition level of the main handler was class 1 for 12% of handlers (90/763), class

2 for 10% (79/763), class 3 for 35% (268/763), participation in national championships for 39% (296/763) and national team for 4% (30/763).

Table 6 Agility dogs in studies I and II. Continuous values are presented as median and interquartile range.

	Non-injured (n=745)	**Injured (n=119)**
Age (years)	4.4 (2.8–6.1)	4.9 (3.3–6.7)
Height (cm)	42 (34–50)	48 (39–53)
Weight (kg)	13 (8–19)	15 (10–20)
Height category		
Extra small	55 (7%)	9 (8%)
Small	151 (20%)	13 (11%)
Medium	180 (24%)	24 (20%)
Small large	162 (22%)	31 (26%)
Large	197 (26%)	42 (35%)
Sex		
Intact female	249 (33%)	32 (27%)
Neutered female	203 (27%)	28 (24%)
Intact male	211 (28%)	41 (34%)
Neutered male	82 (11%)	18 (15%)
Breed		
Border Collie	120 (16%)	28 (24%)
Shetland Sheepdog	83 (11%)	13 (11%)
Australian Shepherd	40 (5%)	5 (4%)
Spanish Waterdog	40 (5%)	6 (5%)
Belgian Shepherd	32 (4%)	9 (8%)
Other	301 (40%)	39 (33%)
Dog's highest competition level		
Class 1	133 (18%)	24 (20%)
Class 2	133 (18%)	20 (17%)
Class 3	257 (35%)	37 (31%)
National championships	205 (28%)	35 (29%)
National team	17 (2%)	3 (3%)

4.1.2 Study III

The study III sample comprised Border Collies. Data were collected from 17 dogs -- eight females and nine males -- after one dog was excluded during the orthopaedic examination. Age of dogs was at mean (± standard deviation) was 4.2 ± 2.1 years and height was 51.8 ± 3.2 cm. The dogs had the following competition levels: class 1 for nine dogs, class 2 for four dogs and class 3 for four dogs.

4.2 Sport-related routines in competition-level agility dogs

Results of study I are presented in following paragraphs. The continuous variables are presented as the median (IQR).

4.2.1 Agility training routines

Training of course-like sequences, comprising a minimum of five obstacles including jumps, began at age of 1.0 year (0.8–1.2, n=735). The jumps were set at competition bar height at 1.5 years (1.3–2.0, n=711). Competing was typically started at 2.2 years (1.8–3.0, n=741).

Sport-related routines were investigated during a year that was unaffected by a sport-related injury. Dogs were trained in agility usually once or twice a week for 5–20 minutes of active agility training time during their training weeks (Figure 6). No difference was observed between summer and winter seasons. The total weekly training time was estimated to be 18 minutes/week (13–25 minutes/week, n=730) during training weeks. The dog's highest achieved competition level was associated with training time ($p<0.001$, n=730): dogs that had been part of a national team trained less (median 10 minutes/week) than class 1 dogs (median 25 minutes/week, $p=0.001$), class 2 dogs (median 19 minutes/week, $p=0.012$) and dogs that had participated in national championships as their highest level (median 18 minutes/week $p=0.043$). Class 1 dogs additionally trained less than class 3 dogs (median 18 minutes/week, $p=0.008$).

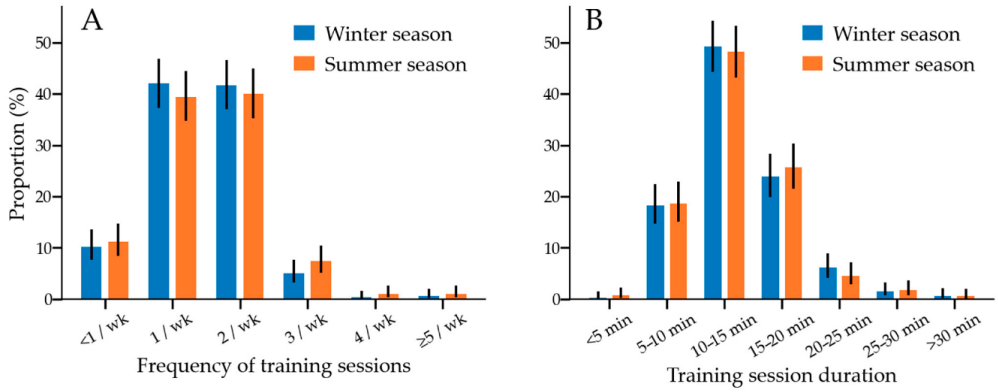


Figure 6 (A) Frequency of agility training sessions per week during summer (n=703) and winter (n=734) season. (B) Duration of agility sessions in active training time during summer (n=702) and winter (n=733) seasons. Error bars indicate the 95% confidence interval. Figure published in Inkilä et al. (2022a).

Bar height relative to wither height was 88% (76–96%, n=744) in training, with taller dogs jumping greater relative bar heights (p<0.001) (Figure 7). Competition level was associated with the bar height in training (p=0.001): dogs in class 1 trained with lower relative bar heights (median 83%) than dogs that had been part of the national team (p = 0.050; median 90%) or had participated in national championships (p = 0.002; median 91%).

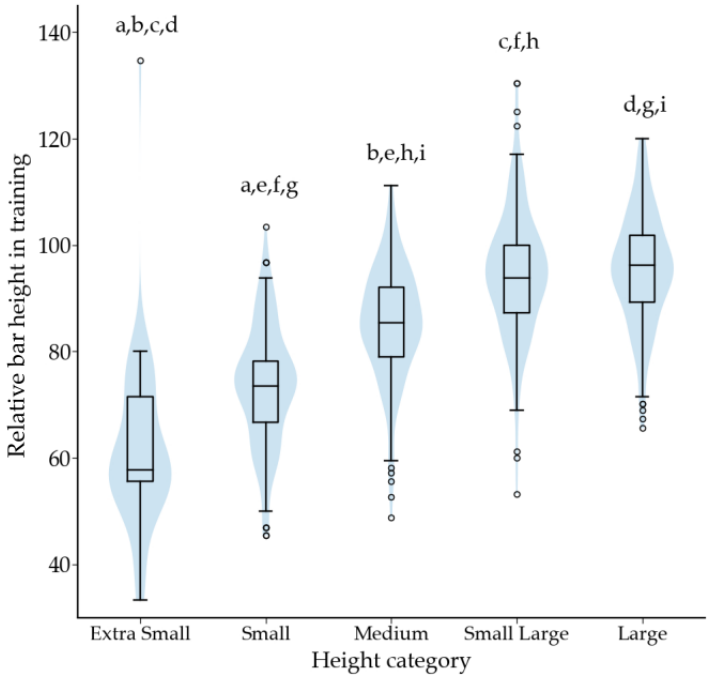


Figure 7 Bar height relative to dog's wither height in training across height categories. A significant difference is indicated by the same letter. For letter a, $p < 0.05$, and for letters b to i $p < 0.001$. Figure published in Inkilä et al. (2022a).

Most dogs (92.9%, 692/745) trained agility during both summer and winter seasons. Dogs that trained during both seasons had a median of four weeks (0–8 weeks, n=678) break from agility during the year. Some dogs (35.4%, 239/678) had no time off from agility during the year.

The most common main surfaces for agility were artificial turf with rubber infill (winter season 47.8% of dogs, summer season 27.2% of dogs), dirt or sand (10.7% and 45.6%), artificial turf without infill (21.3% and 12.4%), and artificial turf with cork infill (14.3% and 8.7%).

4.2.2 Competition routines

Average competition frequency during a year was 2.1 competition runs per month (1.0–3.8 runs per month, n=745). Dogs competing at higher levels competed more frequently ($p<0.001$) (details in Inkilä et al. 2022a), but no difference was observed between height categories. Competition speed of faultless runs was 4.3 m/s (3.9–4.7, n=669). A dog's competition level ($p<0.001$) and height category (<0.001) were associated with competition speed (Figure 8): dogs at the higher competition levels and tall dogs were the fastest.

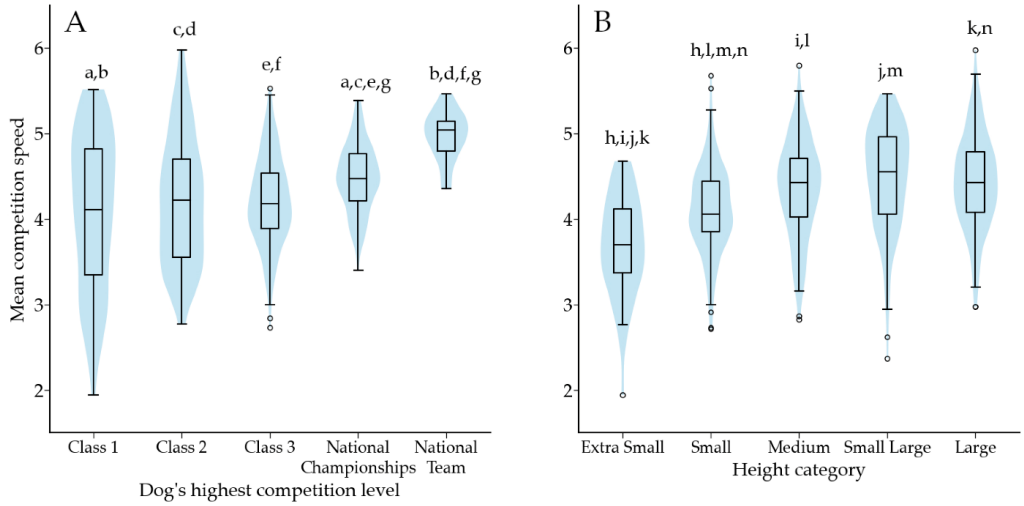


Figure 8 (A) Mean competition speed of faultless runs across competition levels. (B) Mean competition speed of faultless runs across height categories. A significant difference is indicated by the same letter. For letter a, $p < 0.05$, for letters g, h and l $p < 0.01$, and for all other letters $p<0.001$. Figure published in Inkilä et al. (2022a).

The maximum bar height relative to wither height was 103% (95–109%, n=745) in competitions when the bar height's upper range is used. Relative bar heights in training were lower than the maximum bar height in competitions ($p<0.001$, n=744) with 86% of dogs usually training below the maximum competition bar height. The maximum competition bar height relative to wither height increased with the dog's height ($p<0.001$), as in training (details in Inkilä et al. 2022a).

4.2.3 Warm-up and cool-down

Nearly all dogs were warmed up before agility either always (93.4%, 696/745) or usually (6.0%, 45/745). The most common warm-up durations were 10–15 minutes (31.2%, 232/743) and 15–20 minutes (33.6%, 250/743). The warm-up was shorter than 10 minutes for 10.9% of dogs (81/743). Typical elements of a warm-up were exercising on leash (92.9%), exercising off leash (58.3%), dog running (72.8%), walking (67.5%), sprinting (38.6%), tricks (67.2%) and tug play (34.3%) (n=744). The warm-up consisted only of dog walking and/or running on or off leash without any other elements such as tricks, sprints, active stretches or obstacle performances, such as warm-up or surface familiarisation, for 11.0% of dogs (82/744). This type of "non-specific-only" warm-up was not associated with competition level of the dog.

Cool-down was performed either always (86.7%, 646/745) or usually (12.2%, 91/745) with typical durations of 10–15 minutes (26.9%, 200/744) or 15–20 minutes (28.8%, 214/744). The cool-down duration was below 10 minutes for 14.2% of dogs (107/745). Cool-down included exercising the dog on leash (93.4%) and/or off leash (57.0%) with the dog running (70.8%) and/or walking (51.1%) (n=744).

4.2.4 Musculoskeletal care

Regular musculoskeletal care by a professional at least every three months was provided to 62.4% (465/745) of dogs. One-tenth of dogs (9.8%, 73/745) did not receive any musculoskeletal care for one year. Competition level of the dog was associated with regular musculoskeletal care ($p<0.001$, effect size 0.208, n=745): national championship (74.1%) and national team (94.1%) participants were more likely to receive regular care than class 1 (50.4%) or class 2 (53.4%) dogs.

Two-thirds of dogs (67.0%, 499/745) were treated by a massage therapist during one year, typically every two-to-three months (39.7%; 198/499) or less often (43%, 216/499). Half of the dogs (52.1%, 388/745) visited a physiotherapist at least once a year, most commonly either every two-to-three months (37.4%, 145/388) or less often (53.4%, 207/388).

4.2.5 Exercise and conditioning

The median total duration of daily walks was 1.5h (1.3–2.0 h, n=717). Three-quarters of dogs (76.8%, 572/745) performed conditioning exercises to improve strength, speed, endurance, or body control. Only 17.7% of these dogs (101/572) performed conditioning exercises at least twice a week. Almost half of dogs (47.0%, 269/572) did conditioning exercises less often than every two weeks. Exercises were planned by the handler or owner for 70.8% of dogs (405/572) and by a physiotherapist in only 22.4% (128/572).

A quarter of the dogs (24.2%, 180/745) also participated in other physically demanding activities (e.g., canicross, herding, or hunting). Participation in other activities was associated with a dog's competition level (p=0.001, effect size 0.16): national championship (17.6%) and national team (0.0%) participants were less likely to participate in other activities compared to class 1 dogs (33.8%).

4.3 Agility-related injuries

This section presents the study II results. A third of the dogs (33.2%, 278/838) had had at least one agility-related injury when considering the whole agility career at the time of the survey. In the previous full calendar year alone, 13.8% of dogs (119/864) had suffered an agility-related injury. Close to three-quarters of the 119 injured dogs (72.3%, 86/119) had had one agility-related injury during 2019, with the remaining dogs having had multiple injuries. The following text describes the latest injury of the previous full calendar year for each dog.

4.3.1 Anatomical location of injury

According to owners, forelimb injuries were the most common ones (60.5%, 72/119). One-third of the dogs (34.5%, 41/119) injured their neck or back and 19.3% (23/119) suffered an injury to the hindlimb. Figure 9 presents the most commonly injured, detailed anatomical sites. Multiple sites were injured for over a third of the dogs (37.8%, 45/119). Injuries were mainly soft tissue injuries with muscle strain (42.0%, 50/119) and ligament sprain (18.5%, 22/119) the most common injury types. The type of injury was often unclear (18.5%, 22/119). Information on anatomical site and injury type is based on owner reports. Only 41.2% (49/119) were taken to veterinary care due to the injury.

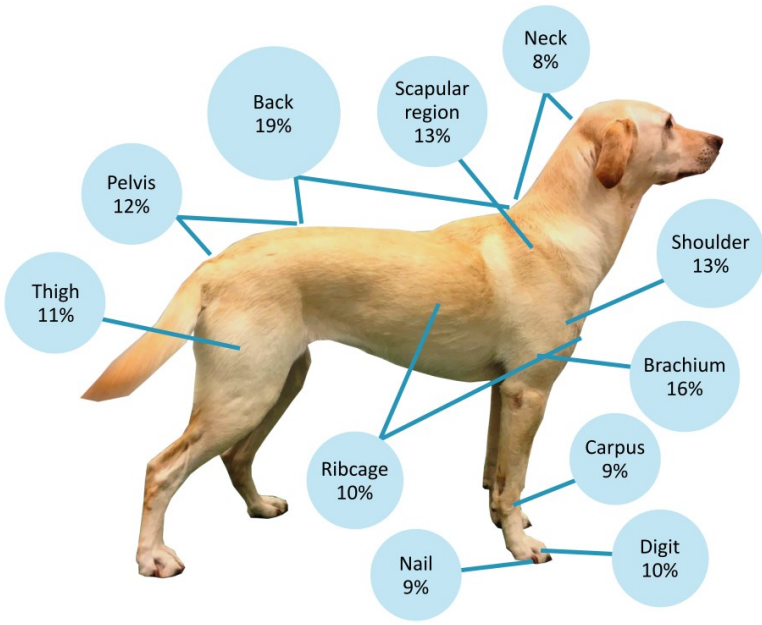


Figure 9 The most common anatomical sites reported to have been injured based on owner reports. A similar figure, with additional sites and without percentages, was provided for survey respondents. Uncommon sites have been removed. Nail and digit refer to forelimbs only. The size of the blue circle is proportional to the percentage.

4.3.2 Context of the injury

Most injuries occurred during agility training (66.9%, 79/118) with the remaining 33.1% (39/119) occurring during competitions. Training-related injuries, for which the timing of the injury was known, occurred typically during the second half of the session (71.7%, 33/46). The rate of competition-related injuries was 1.44 injuries / 1000 competition runs. Competition-related injuries occurred commonly during the second run of the day (47.1%, 16/34), followed by the first run (23.5%, 8/34), third run (14.7%, 5/34) and fourth run (14.7%, 5/34). The majority of injuries (62.3%, 71/114) were recognised after, not during, the agility session.

4.3.3 Obstacle-related injuries

Over half of injuries (56.8%, 67/118) were perceived to be related to obstacle performances. The situation regarding the injury was unknown to the owner in over one-fourth of cases (28.8%, 34/119). Obstacles involving jumping (bar jump, spread jump, tyre, and long jump) were associated with 41.2% (26/63) of the obstacle-related injuries, and 21.8% (26/119) of all injuries. Figure 10 presents the obstacles most often associated with injury.

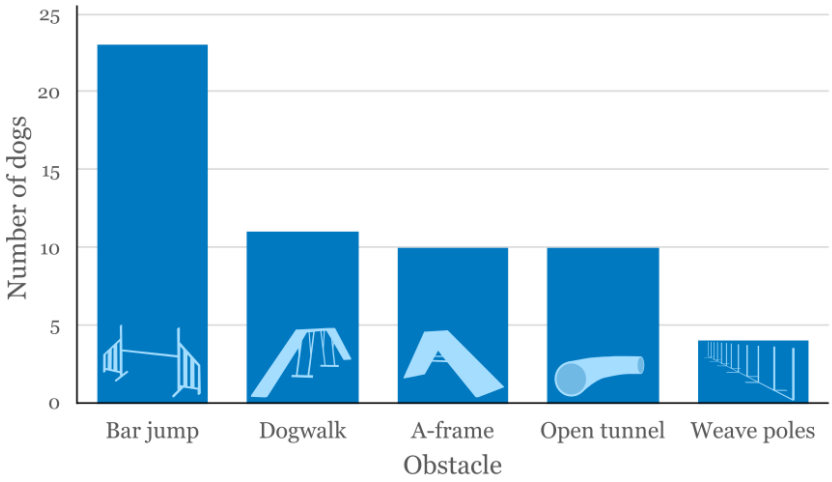


Figure 10 Obstacles most often perceived to be associated with injuries (n=63). Additionally, two dogs were injured in seesaw and one dog on each of the following: spread jump, tyre and long jump.

Collision with an obstacle was considered related to the injury in 29.9% of obstacle-related injuries (20/67). Obstacle category was associated with collisions (p=0.001, n=52): collisions were more common on jump obstacles compared to contact obstacles (OR 0.03, 95% CI 0.00–0.30, p=0.003) and open tunnel and/or weaves (OR 0.05, 95% CI 0.01–0.43, p=0.007). The same regression model also included the dog's competition speed, which was not associated with risk of collision (p=0.547).

Falling from the obstacle was observed in 72.7% (8/11) of dogwalk-associated injuries and in 40.0% (4/10) of A-frame associated injuries. Running contact technique was used by all dogs with A-frame associated injury (100.0%, 9/9). The technique on the dogwalk varied among dogs with dogwalk-associated injury: 60.0% (6/10) of dogs used stopped contact technique, 30.0% (3/10) running contact and 10.0% (1/10) other or in between.

4.3.4 Surfaces and slipping

Injuries occurred commonly (67.6%, 75/111) on a familiar surface on which the dog had performed agility weekly during the three-month period preceding the injury. In total, a third of injured dogs (35.5%, 33/93) had slipped. Surface familiarity refers to the surface material (e.g., dirt), not to a specific agility field or arena. Slipping-related injuries were more common on surfaces that were less familiar for the dogs (not performing agility weekly on the surface) (OR 3.34, 95% CI 1.13–9.88,

p=0.029, n=77). In the same regression model, speed or surface were not associated with slipping.

Many dogs (42.3%, 22/52) with obstacle-related injuries had slipped during obstacle performance (including take-off and landing). Among dogs with obstacle-related injuries, slipping was associated with obstacle category (p=0.012, n=46): slipping occurred more often on jumping obstacles compared to contact obstacles (OR 0.08, 95% CI 0.01–0.86, p=0.037). Risk for slipping during obstacle performance was similar during jumping obstacles and open tunnels and/or weaves (p=0.143). Surface was not associated with slipping during obstacle performance in the same regression model (p=0.517). Slipping between obstacles had been observed in 16.7% of dogs (15/90) with no association with competition speed (p=0.827) or field surface (p=0.323).

4.3.5 Treatment and recovery

Less than half of the dogs (41.2%, 49/119) received veterinary care for their injury. The most-common treatments were exercise restriction (77.1%), medical treatment (46.6%), physiotherapy (42.2%), and rehabilitation/conditioning as part of physiotherapy (21.2%). At median, injured dogs were back to their previous level in agility in four weeks (14–70 days, n=88). One-tenth of injured dogs (9.6%, 11/114) had to retire from the sport due to their injury.

4.4 Risk-factors for agility-related injuries

Twenty-seven variables were associated with agility-related injury during 2019 in univariate models (p<0.1) (details in Inkilä et al. 2022b). A multivariate logistic regression model was developed using these variables. Two variables (previous agility-related injury yes/no, height category) were removed because they were closely related to two more detailed variables (wither height, number of previous agility-related injuries).

Only dogs without missing data for all variables could be included in the development of the model. Three variables (surface, training session frequency and competition speed) had a smaller sample size and were therefore not included in the final model. Rather, three separate subgroup models were created, each including one of the variables with small sample size in addition to variables in the final model. Extreme outliers in three variables (weight ≥31 kg, age at which course-like training was started ≥3.17 years and age at which jumps were set at competition height ≥3.5 years) were pooled to prevent them being overemphasised in the statistical modelling.

Figure 11 presents the final model. The subgroup model for training frequency is presented in figure 12 and the remaining subgroup models are presented in Inkilä

et al. (2022b). The following variables were significant risk factors for agility-related injury during 2019: multiple previous agility-related injuries, finding of lumbosacral transitional vertebra (LTV), older age when starting course-like training, physiotherapy every two-to-three months (compared with never), and high training frequency (>2 sessions/wk). Protective factors included A-frame performance technique (other than stopped or running) and female sex, moderate competition frequency, and participation in other physically demanding sports in some models.

Some of the previously-mentioned variables could be considered to remain constant during a dog's agility career. Their association with agility-related injuries any time before their survey participation was evaluated with univariate logistic regression. Neither LTV ($p=0.121$), age when starting course-like training ($p=0.919$), nor sex ($p=0.185$) were associated with agility-related injury when all injuries until the time of survey participation were included.

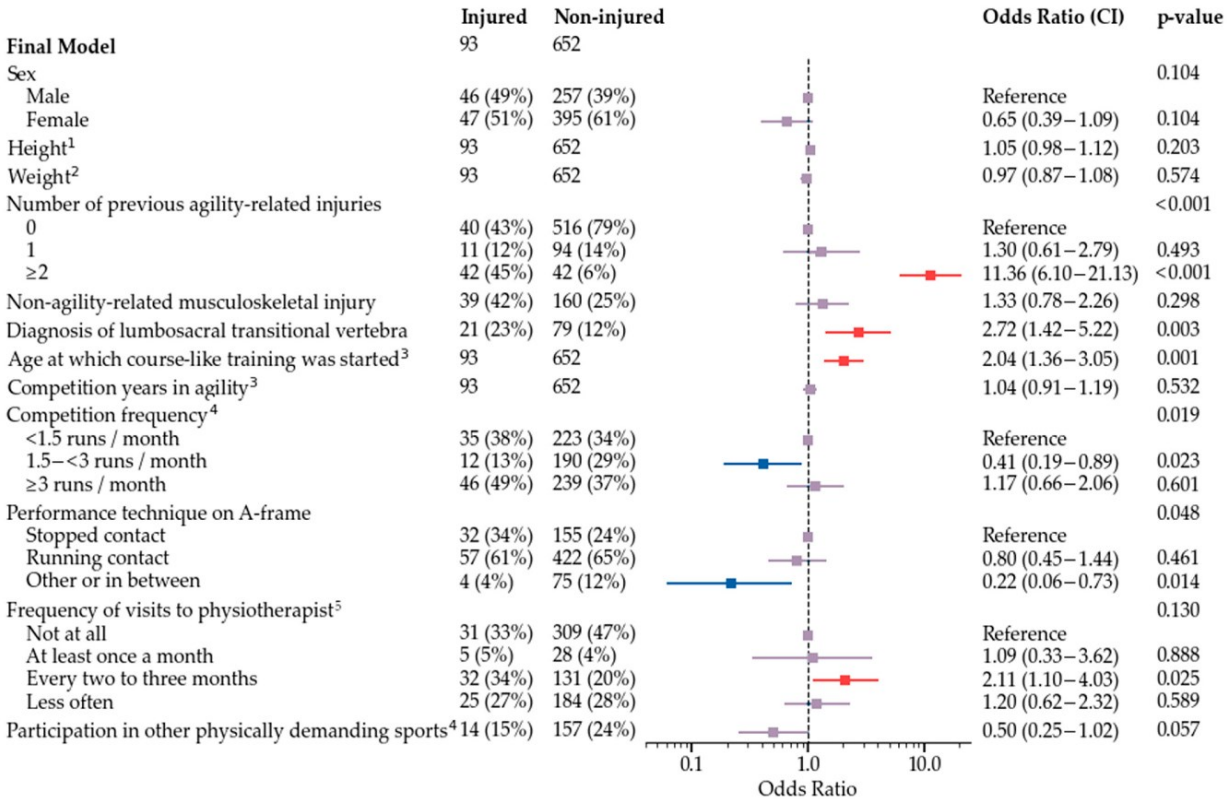


Figure 11 Final multivariate model for odds of agility-related injury during 2019. Significant risk factors are indicated in red and protective factors in blue. 1 For a one-centimeter increase, the odds increase by OR. 2 For a one-year increase, the odds increase by OR. 3 For a one-year increase, the odds increase by OR. 4 Routines during the three-month period preceding injury in injured dogs and during 2019 in non-injured dogs. 5 Routines during the one-year period preceding injury in injured dogs and during 2019 in non-injured dogs. Figure published in Inkilä et al. (2022b).

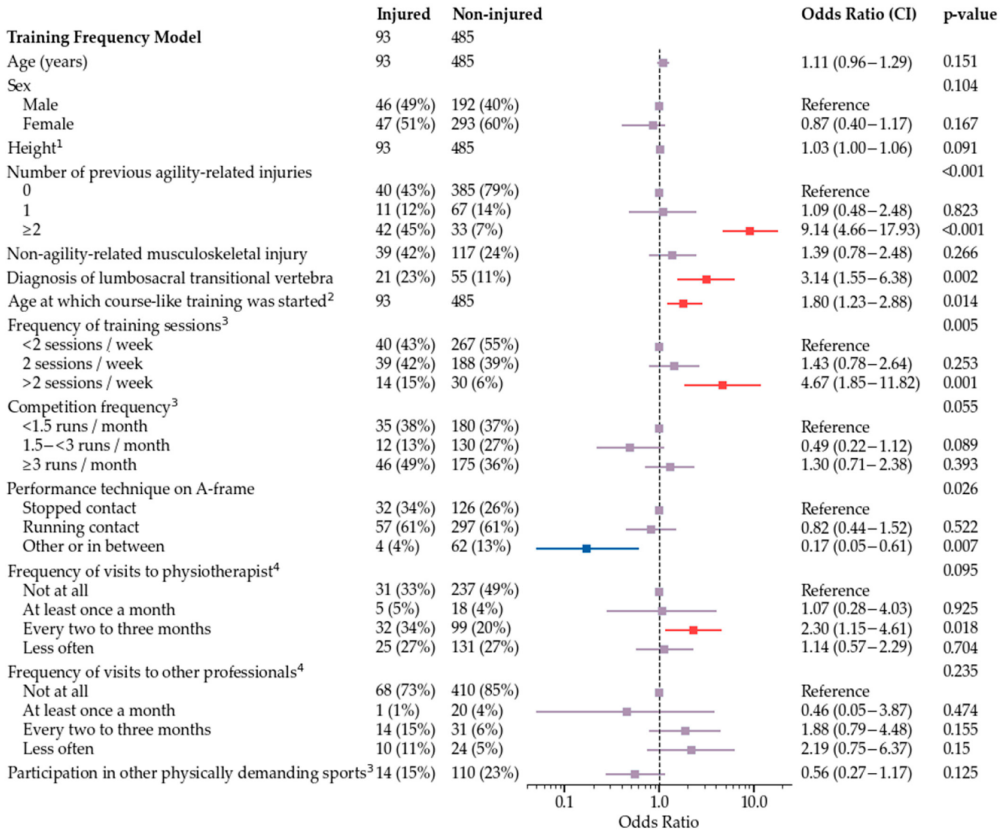


Figure 12 Training frequency model for odds of agility-related injury during 2019. Significant risk factors are indicated in red and protective factors in blue. [1] For a one-centimeter increase, the odds increase by OR. [2] For a one-year increase, the odds increase by OR. [3] Routines during the three-month period preceding injury in injured dogs and during 2019 in non-injured dogs. [4] Routines during the one-year period preceding injury in injured dogs and during 2019 in non-injured dogs. Figure published in Inkilä et al. (2022b).

4.5 Effect of bar height on jumping biomechanics at take-off

This section presents results of study III. In total, 176 take-offs to a jump were analysed: 56 to 63 at each of the three bar heights (80%, 100% and 120% of a dog's wither height). In the following results, the effects have been evaluated in a model that is adjusted for the number of approach strides.

4.5.1 Effect of bar height on velocity, impulses and jump arch

The increase in bar height reduced horizontal velocity at approach (trailing forelimb touch-down) and lift-off (leading hindlimb limb lift-off) (Table 7): the differences between lowest and highest bar heights were -0.4–(-0.9) m/s ($p<0.001$ for approach and lift-off) with velocities of individual trials ranging from 5.3 m/s to 8.2 m/s. The difference was greater at 120% bar height, because the net cranio-caudal impulse produced during take-off shifted from accelerative to decelerative when the bar height increased (Table 8). The net cranio-caudal impulse produced by the hindlimb pair remained accelerative at all heights but reduced in magnitude (Table 8). The close-to-zero net impulse by the forelimb pair at the lowest bar height reduced to clearly decelerative as the height increased (Table 8). The changes in the cranio-caudal impulses as well as the increase in the vertical impulse in both pairs of limbs led the resultant force vector angle to decrease in both pairs of limbs (Table 8), meaning that the forces produced during take-off were directed more steeply upwards (rather than forwards) as the bar height increased. This resulted in a steeper take-off angle with the increasing bar height (Table 7). Additionally, the dogs positioned their trunks into a steeper, more upwards oriented angle at lift-off (Table 7). The distribution of the vertical impulse on the fore- and hindlimbs was unaffected by the bar height. Figure 13 presents the mean curves of the vertical forces.

The take-off distance at the 80% bar height was the estimated at a mean of 8 to 9 cm further away from the obstacle compared to the higher bar heights ($p\leq0.010$). As expected, the calculated peak height of the trunk increased with the increasing bar height (Table 7). However, the bar clearance (difference between peak height and bar height) was additionally affected by the bar height: there was a lower bar clearance at 100% height (42% of wither height) compared to 80% height (48%, $p<0.001$) and 120% height (49%, $p<0.001$). Thus, the peak height of the trunk over the jump was markedly higher at 120% of bar height (difference to 100% bar height was 27% of wither height), whereas the peak trunk heights were closer to each other at the two lower bar heights (the difference between 80% and 100% bar heights was 13% of wither height).

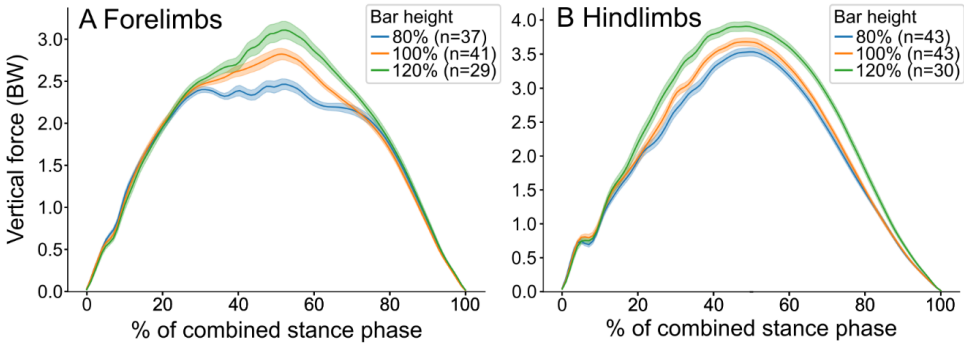


Figure 13 Vertical ground reaction forces from the forelimbs (A) and hindlimbs (B) stance phase at take-off to a jump. Mean curves ± standard error of mean from all trials at three bar heights are presented: 80% (blue), 100% (orange), and 120% (green) of wither height. The x-axis refers to the combined stance time of the limb pair starting from touch-down of the trailing limb and ending at lift-off of the leading limb. Thus, the forces from the trailing and leading limbs are summed and therefore overlapping with each other. Only trials where there was no overlap with a previous stride or between the fore- and hindlimbs are included in this figure. The effect of the stride number is not controlled in this figure. The number of trials per dog per bar height varied.

Table 7 Linear mixed model results: effect of the bar height and the approach stride number on the jump arch and limb coordination at the take-off in agility dogs. Table adapted from Inkilä et al. (2024).

SE = standard error, ICC = intraclass correlation coefficient, FLs = forelimbs, HLs = hindlimbs, TrFL = trailing forelimb, LeFL = leading forelimb, TrHL = trailing hindlimb, LeHL = leading hindlimb.

The main effects for the bar height and the stride number are presented as p-values along with estimated marginal means for all bar heights. A different shade of orange background indicates a significant difference ($p<0.05$) between the bar heights. A white background indicates no differences between the bar heights. An estimated difference between the highest and lowest bar height is presented. Estimates for other pairwise comparisons and for the stride number can be found in Inkilä et el. (2024). [a] Lower value indicates greater synchronicity.

		Main effect Bar height	Estimated marginal mean ± SE Bar height			Difference between 80% and 120% bar heights		Main effect Stride number		ICC
	n	p	80%	100%	120%	Estimate ± SE	p	p	Difference	
Horizontal velocity at approach (m/s)	161	<0.001	7.27 ± 0.11	7.15 ± 0.11	6.86 ± 0.11	-0.41 ± 0.04	<0.001	<0.001	2<1	81
Horizontal velocity after lift-off (m/s)	173	<0.001	7.29 ± 0.14	7.11 ± 0.14	6.60 ± 0.14	-0.69 ± 0.05	<0.001	<0.001	2<1	80
Take-off distance (cm)	174	0.012	192 ± 9	183 ± 9	183 ± 9	-9 ± 3	0.009	<0.001	2<1	81
Trunk angle at lift-off (°)	161	<0.001	15.0 ± 0.7	16.8 ± 0.7	20.9 ± 0.7	5.8 ± 0.4	<0.001	0.001	2<1	59
Take-off angle (°)	154	<0.001	10.7 ± 0.6	12.9 ± 0.6	17.2 ± 0.5	6.5 ± 0.3	<0.001	0.071		61
Peak height of trunk over the jump (% of wither height)	173	<0.001	128.9 ± 3.2	141.8 ± 3.2	168.3 ± 3.2	39.4 ± 1.5	<0.001	<0.001	2<1	71
Bar clearance (% of wither height)	173	<0.001	48.9 ± 3.2	41.8 ± 3.2	48.3 ± 3.2	-0.6 ± 1.5	0.696	<0.001	2<1	71
Stance time										
Trailing forelimb (ms)	176	<0.001	82 ± 3	84 ± 3	91 ± 3	9 ± 1	<0.001	0.799		83
Leading forelimb (ms)	176	<0.001	75 ± 2	77 ± 2	80 ± 2	5 ± 1	<0.001	<0.001	2<1	71
Trailing hindlimb (ms)	176	<0.001	79 ± 2	80 ± 2	84 ± 2	5 ± 1	<0.001	0.525		73
Leading hindlimb (ms)	176	<0.001	74 ± 2	75 ± 2	80 ± 2	6 ± 1	<0.001	0.778		64
Synchronicity										
Forelimbs (% of TrFL stance time)a	176	<0.001	56.4 ± 1.9	54.2 ± 1.9	50.3 ± 1.9	-6.1 ±1.1	<0.001	0.010	2<1	58
Hindlimbs (% of TrHL stance time)a	176	<0.001	22.7 ± 2.4	19.7 ± 2.4	13.1 ± 2.4	-9.6 ± 1.1	<0.001	<0.001	2<1	73

		Main effect Bar height	Estimated marginal mean ± SE Bar height			Difference between 80% and 120% bar heights		Main effect Stride number		ICC
	n	p	80%	100%	120%	Estimate ± SE	p	p	Difference	
Distance between limbs at TD										
Craniocaudal distance between FLs (cm)	173	<0.001	35.2 ± 1.3	33.9 ± 1.3	31.8 ± 1.3	-3.5 ± 0.7	<0.001	<0.001	2<1	67
Craniocaudal distance between HLs (cm)	173	<0.001	13.5 ± 1.5	11.5 ± 1.4	7.3 ± 1.5	-6.2 ± 0.7	<0.001	<0.001	2<1	74
Craniocaudal distance between LeFL and TrHL (cm)	173	<0.001	12.6 ± 1.3	11.1 ± 1.2	7.4 ± 1.2	-5.1 ± 0.7	<0.001	<0.001	2<1	59
Mediolateral distance between FLs (cm)	173	<0.001	8.0 ± 0.7	8.4 ± 0.6	9.4 ± 0.7	1.4 ± 0.3	<0.001	0.462		73
Mediolateral distance between HLs (cm)	173	<0.001	12.7 ± 0.5	13.0 ± 0.5	14.2 ± 0.5	1.5 ± 0.2	<0.001	<0.001	1<2	76
Craniocaudal distance between TrHL and trunk marker (cm)	173	<0.001	6.3 ± 0.6	5.9 ± 0.5	4.4 ± 0.5	-1.9 ± 0.3	<0.001	<0.001	1<2	57
Craniocaudal distance between LeHL and trunk marker (cm)	174	<0.001	5.9 ± 0.5	5.4 ± 0.5	4.1 ± 0.5	-1.8 ± 0.4	<0.001	<0.001	1<2	41

Table 8 Linear mixed model results: effect of the bar height and the approach stride number on kinetics at the take-off to a jump in agility dogs. Table adapted from Inkilä et al. (2024).

SE = standard error, ICC = intraclass correlation coefficient, BW = body weight, FLs = forelimbs

The main effects for the bar height and the stride number are presented as p-values along with estimated marginal means for all bar heights. A different shade of orange background indicates significant difference ($p<0.05$) between bar heights. A white background indicates no differences between bar heights. An estimated difference between the highest and lowest bar height is presented. Estimates for other pairwise comparisons and for the stride number can be found in Inkilä et el. (2024).

		Main effect Bar height	Estimated marginal mean ± SE Bar height			Difference between 80% and 120% bar heights		Main effect Stride number		ICC
	n	p	80%	100%	120%	Estimate ± SE	p	p	Difference	
Forelimbs										
Vertical impulse (BWs)	158	<0.001	0.207 ± 0.005	0.216 ± 0.005	0.235 ± 0.005	0.028 ± 0.003	<0.001	<0.001	2<1	66
Net craniocaudal impulse (BWs)	158	<0.001	0.001 ± 0.002	-0.003 ± 0.002	-0.015 ± 0.002	-0.017 ± 0.001	<0.001	<0.001	2<1	58
Direction of resultant force vector (°)	158	<0.001	90.4 ± 0.5	89.2 ± 0.5	86.4 ± 0.5	-4.0 ± 0.3	<0.001	<0.001	2<1	61
Hindlimbs										
Vertical impulse (BWs)	163	<0.001	0.182 ± 0.003	0.188 ± 0.003	0.207 ± 0.003	0.024 ± 0.002	<0.001	<0.001	2<1	43
Net craniocaudal impulse (BWs)	163	<0.001	0.017 ± 0.002	0.012 ± 0.002	0.007 ± 0.002	-0.010 ± 0.001	<0.001	<0.001	2<1	68
Direction of resultant force vector (°)	163	<0.001	95.4 ± 0.5	93.7 ± 0.5	92.0 ± 0.5	-3.4 ± 0.3	<0.001	<0.001	2<1	65
All four limbs										
Vertical impulse (BWs)	163	<0.001	0.391 ± 0.007	0.405 ± 0.007	0.443 ± 0.007	0.052 ± 0.004	<0.001	<0.001	2<1	59
Net craniocaudal impulse (BWs)	163	<0.001	0.018 ± 0.003	0.008 ± 0.003	-0.008 ± 0.003	-0.026 ± 0.002	<0.001	<0.001	2<1	54
Weight distribution (% of vertical impulse on FLs)	156	0.340	53.0 ± 0.6	53.5 ± 0.6	53.2 ± 0.6	0.2 ± 0.3	0.532	0.011	2<1	60

4.5.2 Effect of bar height on limb coordination

Paw placements at take-off were also influenced by the bar height. The synchronicity between the trailing and leading limbs increased in both pairs of limbs as the height increased (Table 7), meaning that the leading limb contacted the ground sooner after the trailing limb. The cranio-caudal distance between the trailing and leading limbs decreased with increasing the bar height by 3.5 cm in the forelimbs and 6.2 cm in the hindlimbs from the lowest to highest bar height ($p<0.001$) (Table 7). Additionally, the cranio-caudal distance between the leading forelimb and trailing hindlimb decreased by 5.1 cm ($p<0.001$) (Table 7). Thus, all limbs were positioned closer to each other in the cranio-caudal direction. The medio-lateral distance, however, was 1.4 cm (forelimbs) to 1.5 cm (hindlimbs) greater at the 120% bar height compared to the lowest bar height ($p<0.001$) (Table 7).

At all bar heights, the hindlimb paws were placed caudal to the trunk marker (midway between markers on 11th rib on both sides of the dog) at touch-down, when hindlimb paw first contacted the ground before pushing off the ground. However, the distance was decreased by 1.8 to 1.9 cm at the 120% bar height compared to the lowest bar height ($p<0.001$) (Table 7). The stance time of each limb was additionally longer at the highest bar height compared to lower bar heights (Table 7).

4.5.3 Effect of bar height on sagittal joint angles

Figures 14 and 15 depict limb joint angles during the stance phase of each limb. In the most distal joints, the carpus and tarsus, the range of motion (ROM) was 3.1 to 4.5 degrees greater at the 120% bar height compared to the lowest bar height ($p<0.1$). This was due to the greater peak extension angles in the carpal joints of the trailing and leading forelimbs (Table 9). Both tarsal joints, however, had greater peak flexion at the 120% bar height with some additional effect of peak extension of the leading hindlimb (Table 9). The trailing forelimb elbow showed greater peak flexion by 5.3 degrees and ROM by 3.4 degrees at the highest bar height compared to the lowest bar heights (Table 9).

The effects, in degrees of change, were smaller in other joints. Both stifle joints had a slightly greater ROM by 1.8 to 2.4 degrees at the 120% bar height than at the 80% bar height – in the trailing hindlimb due to greater peak extension and in the leading hindlimb due to greater peak flexion (Table 9). The trailing forelimb shoulder and trailing hindlimb hip joint had increased ROM at the 120% bar height with a 3.2 to 3.8 difference to the 80% bar height (Table 9). The shoulder joint was more extended and the hip joint more flexed at the highest bar height (Table 9). No effects were seen in the leading limb shoulder and hip joints.

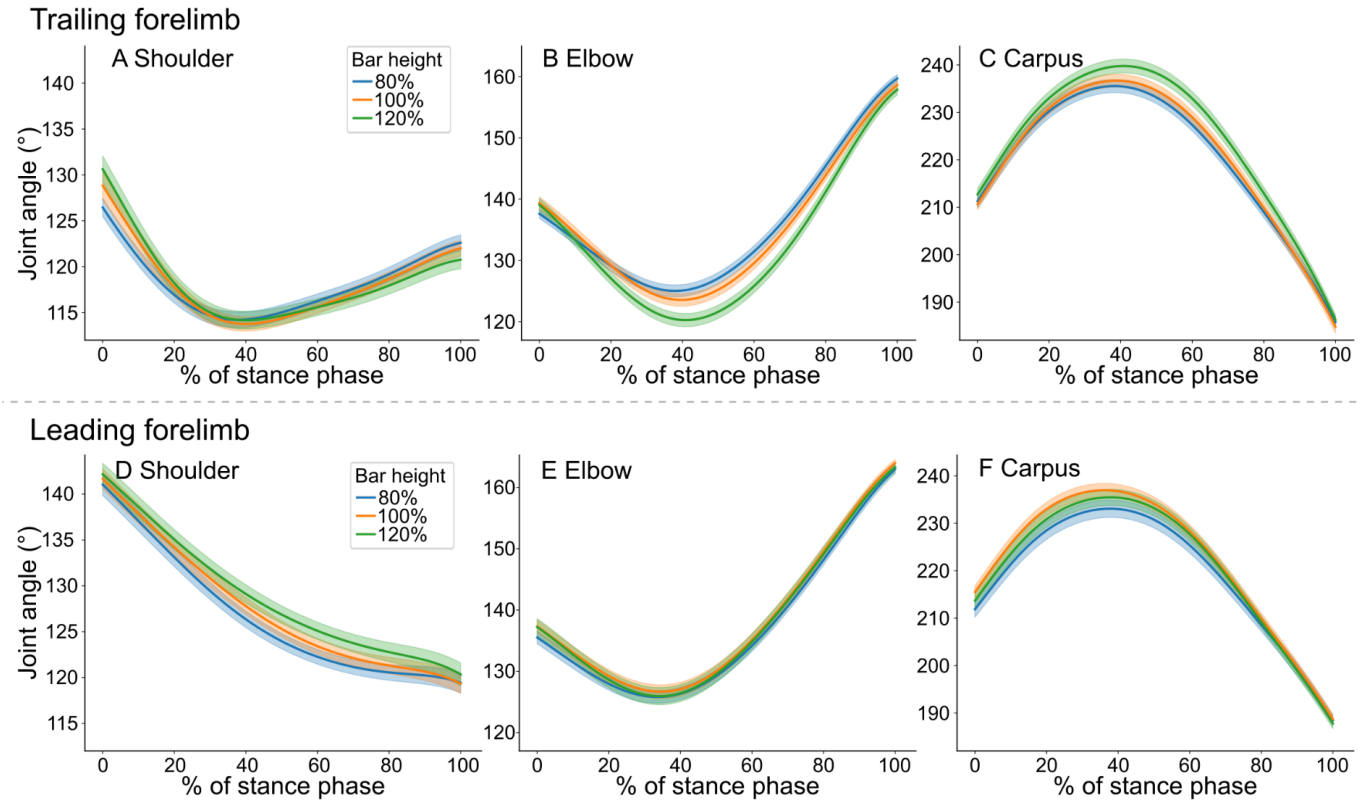


Figure 14 Sagittal joint angles in trailing (A–C) and leading (D–F) forelimbs during the stance phase at take-off to a jump. Joint angles of shoulder (A, D), elbow (B, E), and carpus (C, F) are shown. Mean curves ± standard error of mean from all trials at three bar heights are presented: 80% (blue), 100% (orange), and 120% (green) of wither height. Please note that the y-axis is scaled to each figure and that the effect of the stride number is not controlled in this figure. The number of trials per dog per bar height varied from 0 to 7. Figure adapted from Inkilä et al. (2024).

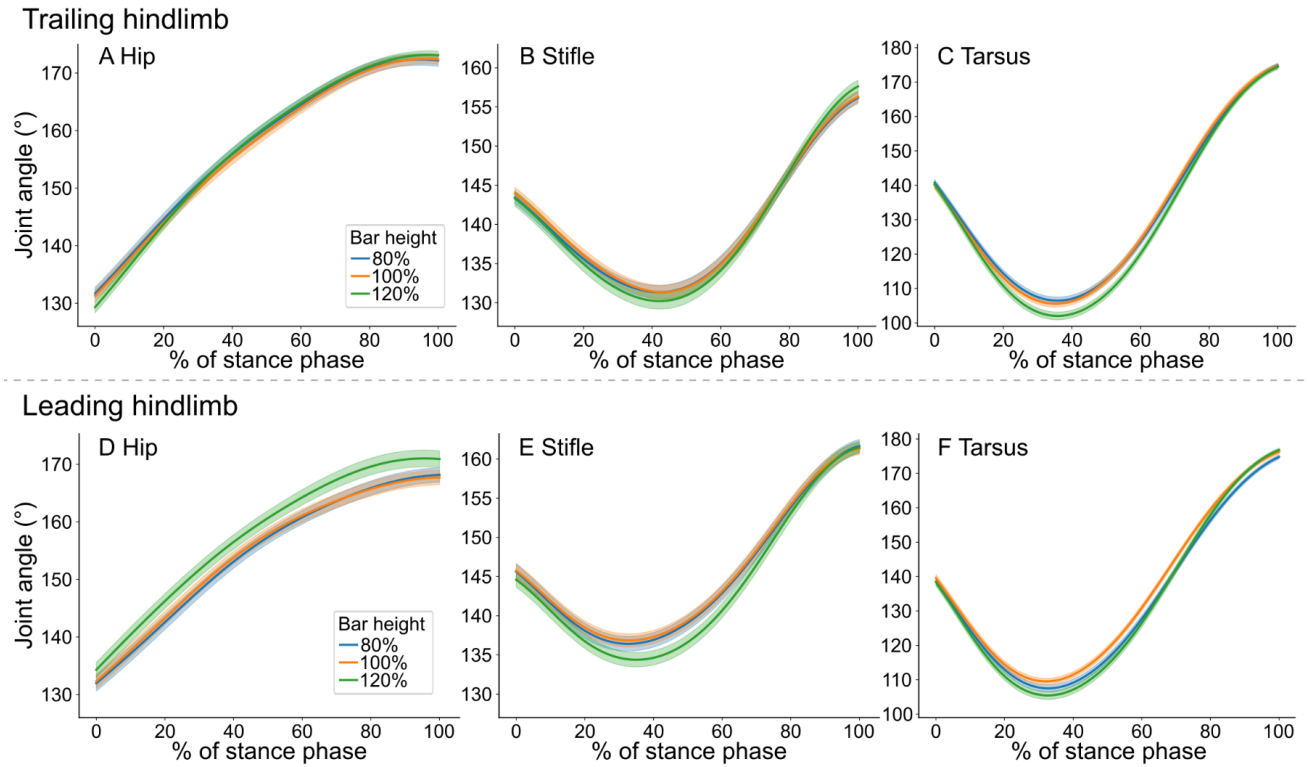


Figure 15 Sagittal joint angles in trailing (A–C) and leading (D–F) hindlimbs during the stance phase at take-off to a jump. Joint angles of hip (A, D), stifle (B, E), and tarsal (C, F) joints are shown. Mean curves ± standard error of mean from all trials at three bar heights are presented: 80% (blue), 100% (orange), and 120% (green) of wither height. Please note that the y-axis is scaled to each figure and that the effect of the stride number is not controlled in this figure. The number of trials per dog per bar height varied from 0 to 7. Table adapted from Inkilä et al. (2024).

Table 9 Linear mixed model results: effect of the bar height and the approach stride number on sagittal joint kinematics at the take-off to a jump in agility dogs. Table adapted from Inkilä et al. (2024).

SE = standard error, ICC = intraclass correlation coefficient, ROM = range of motion

The main effects for the bar height and the stride number are presented as p-values along with an estimated marginal means for all bar heights. A different shade of orange background indicates a significant difference ($p<0.05$) between the bar heights. A white background indicates no differences between the bar heights. An estimated difference between the highest and lowest bar height is presented. Estimates for other pairwise comparisons and for the stride number can be found in Inkilä et el. (2024). Only variables where the bar height had an effect are presented here.

		Main effect Bar height	Estimated marginal mean ± SE Bar height			Difference between 80% and 120% bar heights		Main effect Stride number		ICC
	n	p	80%	100%	120%	Estimate ± SE	p	p	Difference	
Trailing forelimb										
Shoulder peak extension (°)	167	<0.001	128.2 ± 2.1	129.2 ± 2.1	131.2 ± 2.1	3.0 ± 0.6		<0.001		88
Shoulder ROM (°)	167	<0.001	13.3 ± 1.4	14.7 ± 1.4	17.2 ± 1.4	3.8 ± 0.7	<0.001	0.67		68
Elbow peak flexion (°)	168	<0.001	124.5 ± 2.0	122.7 ± 2.0	119.2 ± 2.0	-5.3 ± 0.8	<0.001	0.003	1<2	78
Elbow peak extension (°)	168	0.014	159.5 ± 1.2	158.4 ± 1.2	157.6 ± 1.2	-1.9 ± 0.6	<0.001	0.134		66
Elbow ROM (°)	168	<0.001	34.8 ± 1.0	35.5 ± 1.0	38.1 ± 1.0	3.4 ± 0.7	0.004	0.058		48
Carpus peak extension (°)	171	0.002	234.7 ± 2.9	235.6 ± 2.9	238.1 ± 2.9	3.4 ± 1.0	<0.001	0.213		84
Carpus ROM (°)	171	0.007	50.4 ± 1.5	51.6 ± 1.5	53.7 ± 1.5	3.3 ± 1.0	0.002	0.148		48
Leading forelimb										
Shoulder peak flexion (°)	171	0.040	118.8 ± 2.0	120.1 ± 1.9	119.7 ± 1.9	0.9 ± 0.5	0.085	0.251		89
Carpus peak extension (°)	172	0.017	230.2 ± 3.1	233.0 ± 3.1	232.5 ± 3.1	2.3 ± 1.0	0.027	<0.001	2<1	84
Carpus ROM (°)	172	0.018	43.1 ± 2.1	45.7 ± 2.1	46.3 ± 2.1	3.1 ±1.2	0.008	<0.001	2<1	63
Trailing hindlimb										
Hip peak flexion (°)	172	<0.001	129.8 ± 1.9	129.7 ± 1.9	127.4 ± 1.9	-2.4 ± 0.7	<0.001	<0.001	2<1	80
Hip ROM (°)	172	<0.001	41.6 ± 1.1	42.1 ± 1.1	44.7 ± 1.1	3.2 ± 0.6	<0.001	0.141		63
Stifle peak extension (°)	172	<0.001	155.9 ± 1.3	156.1 ± 1.3	157.6 ± 1.3	1.7 ± 0.4	<0.001	0.949		84

		Main effect Bar height	Estimated marginal mean ± SE Bar height			Difference between 80% and 120% bar heights		Main effect Stride number		ICC
	n	p	80%	100%	120%	Estimate ± SE	p	p	Difference	
Stifle ROM (°)	172	0.001	25.3 ± 0.9	25.2 ± 0.8	26.7 ± 0.8	2.4 ± 0.8	0.002	0.107		31
Tarsus peak flexion (°)	172	<0.001	107.6 ± 1.8	106.0 ± 1.8	102.9 ± 1.8	-4.6 ±0.9	<0.001	<0.001	1<2	65
Tarsus ROM (°)	172	<0.001	67.0 ± 1.2	68.4 ± 1.2	71.5 ± 1.2	4.5 ± 0.8	<0.001	<0.001	2<1	47
Leading hindlimb										
Hip peak extension (°)	172	0.022	168.2 ± 2.4	169.1 ± 2.4	170.4 ± 2.4	2.2 ± 0.8	0.006	0.054		82
Stifle peak flexion (°)	172	<0.001	135.0 ± 1.4	135.8 ± 1.4	133.1 ± 1.4	-2.0 ±0.7	0.009	0.101		
Stifle ROM (°)	172	<0.001	26.0 ± 0.8	25.0 ± 0.8	27.8 ± 0.8	1.8 ± 0.6	0.002	0.801		85
Tarsus peak flexion (°)	172	<0.001	107.7 ± 1.7	109.2 ± 1.7	105.3 ± 1.7	-2.4 ± 1.0	0.016	0.437		60
Tarsus peak extension (°)	172	0.002	175.2 ± 1.0	176.0 ± 1.0	176.9 ± 1.0	1.7 ± 0.5	<0.001	0.350		67
Tarsus ROM (°)	172	<0.001	67.4 ± 1.6	66.7 ± 1.6	71.5 ± 1.6	4.1 ± 0.9	<0.001	0.178		84

4.5.4 Effect of approach stride number on take-off biomechanics

Take-off to the second jump in a sequence of three straight-line jumps was measured. The number of gallop strides between obstacles 1 and 2 (approach stride number) varied: the dog took one stride in two-thirds of the trials (67%, 118/176) and two strides in one-third. The approach stride number and the bar height were not associated ($p=0.74$). Most dogs (53%, 9/17) always used the one-stride approach, 29% (5/17) varied their striding and 18% always used the two-stride approach.

The approach stride number affected the biomechanics of the take-off (tables 7–10). The following results have been adjusted for the effect of bar height. The estimates for differences and estimated marginal means are presented with ± standard error. Compared to the two-stride approach, with a one-stride approach dogs took off an estimated 74 ± 6 cm further away from the jump ($p<0.001$) at an estimated marginal mean of 223 ± 9 cm. They additionally approached (estimate 0.55 ± 0.08 m/s) and took off (estimate 0.36 ± 0.09 m/s) at a greater horizontal velocity ($p<0.001$). The peak height over the jump was greater with the one-stride approach than with the two-stride approach (estimate 17.3 ± 2.5 % of wither height, $p<0.001$).

The vertical impulse was increased with the one-stride approach (estimates forelimbs 0.044 ± 0.005 BWs, hindlimbs 0.020 ± 0.003 BWs, $p<0.001$) and the net cranio-caudal more accelerative (estimate forelimbs 0.009 ± 0.002 BWs, hindlimbs 0.007 ± 0.001 BWs, $p<0.001$). Weight was shifted more to the forelimbs when using the one-stride approach compared to the two-stride approach (estimate 1.4 ± 0.5 %, $p=0.011$).

The ROM values of limb joints during the stance phase were additionally affected by the stride number. The ROM in the forelimb joints was affected by the stride number only in the leading forelimb, where the shoulder (estimate 4.0 ± 1.0°, $p<0.001$), elbow (estimate 6.2 ± 1.5°, $p<0.001$) and carpal joint (estimate 9.0 ± 2.1°, $p<0.001$) ROM were greater with the one-stride approach. The tarsal joint ROM of the trailing hindlimb was greater with the one-stride approach (estimate 7.0 ± 1.4°, $p<0.001$) and the hip joint ROM of the leading hindlimb decreased with the one-stride approach (estimate -3.6 ± 1.4°, $p=0.010$).

5 Discussion

These studies deepen our understanding of agility dogs' routines, injuries, and jumping biomechanics. Study I provided an overview of the training, competition, and management routines of competition-level Finnish agility dogs, shedding light on the differences across competition levels and height categories. These insights are valuable for professionals involved with agility dogs by offering knowledge of the typical routines of these sport dogs. Study II highlighted that agility dogs are prone to forelimb and back injuries and that incidents such as collisions, slips and falls are perceived as causes of injuries by owners. Novel risk and protective factors were revealed in this sample of Finnish competition-level agility dogs, offering a basis for future research. Additionally, study III on the dogs' jumping biomechanics showed that increased bar heights lead to an increase in the range of motion of multiple limb joints, potentially contributing to injuries. This research on agility dog routines, injuries, and biomechanics forms the basis for discussion on the welfare implications of the sport.

5.1 Life of an agility dog

This study evaluated the variation in sport-related routines across competition levels and height categories. Study I provided the largest sample of European agility dogs as of today, whereas other studies have included mainly or exclusively North American agility dogs (Cullen et al., 2013b; Dinallo et al., 2017; Jimenez et al., 2022; Pechette Markley et al., 2022) or a smaller sample of European dogs (Essner, Hesbach, et al., 2022). This chapter discusses the routines of these Finnish dogs in relation to previous results and possible welfare implications.

5.1.1 Training of young agility dogs

The Finnish agility dogs in our sample started training sequences of multiple obstacles typically at one year old. Based on our results and a previous study consisting mainly of North American dogs (Pechette Markley et al., 2022), it appears common worldwide to set bars at full competition bar heights when the dog is 18 months and to start competing at around two years old. Our data revealed that a dog competing at higher levels had often started training and competing at an

earlier age. It might be that early introduction to sport-specific training could be advantageous for future performance. However, a more likely explanation is that competitive handlers are more likely to start training early and to achieve competitive success – possibly without any actual link between the latter two.

Factors relating to a dog and/or handler having high-level competition experience have been associated with higher injury risk in previous studies (Evanow et al., 2021; Sellon et al., 2018; Sundby et al., 2022). Starting training earlier could contribute to the injury risk in these dogs. Indeed, starting jump training at a younger age increased odds of injury in a previous study – although results were opposite for starting weaves or seesaw training (Pechette Markley et al., 2022). Those who started training sequences of jumps at an older age in our sample had higher odds of agility-related injury during the evaluated calendar year. However, start age was not associated with agility-related injury when all injuries during a dog's career were considered. Thus, it is very uncertain whether any actual relationship exists between the two. Additionally, the age at which training begins may not be the most significant factor; the content and amount of training could have a greater impact. Evidence-based suggestions for training of young agility dogs currently cannot be concluded. Guidance can be drawn from research in humans and horses, with insights explored in the following sections.

5.1.1.1 Sport and exercise in growing animals

Tissues of growing animals adapt well to exercise, which can be protective and beneficial long-term (Barneveld & van Weeren, 1999; Kasashima et al., 2002; Logan & Nielsen, 2021; Smith et al., 1999). Restricting foals from exercise delayed cartilage development with possibly lifelong effects (Brama et al., 2002). Beagle puppies running up to 4 km/day showed beneficial joint cartilage adaptations (Kiviranta et al., 1988). However, strenuous exercise can be harmful: young Beagles running up to 20 km/day or 40 km/day had depletion of glycosaminoglycans, a key component of functional cartilage, in their stifle joints (Arokoski et al., 1993; Kiviranta et al., 1992). Intense gallop bouts for foals, that were otherwise confined, led to detrimental changes to cartilage and tendons, while pasture housing had beneficial effects (Barneveld & van Weeren, 1999). Based on this reasoning, voluntary, mainly aerobic exercise could be most beneficial for growing canines as well.

Human studies show exercise benefits, recommending at least 60 minutes of daily moderate-to-vigorous intensity activity for children (World Health Organization, 2020). Most exercise should be aerobic, with muscle and bone-strengthening activities like jumping recommended at least three times a week (World Health Organization, 2020). In young children, moderate-to-vigorous physical activity positively correlates with the development of fundamental motor

skills that serve as building blocks of more complex movements (Jones et al., 2020). This suggests that exercise during early development is also important for future sports skills.

Human youth athletes can suffer sport-related injuries, especially with early specialisation in one discipline (Bell et al., 2018; Carder et al., 2020). Early sport specialisation does not improve performance in various motor and neuromuscular control tasks and could hinder development of motor skills compared to multidisciplinary sport participation (Kliethermes et al., 2020; Myer et al., 2016). Competitive success at the elite level can additionally be achieved without early specialisation (Güllich et al., 2022; Kliethermes et al., 2020). Therefore, participation in a variety of sports and providing opportunities for free, unstructured play are recommended for young humans (Myer et al., 2016). Neuromuscular training programs also lower sport injury risk in young human athletes (Rössler et al., 2014; Steib et al., 2017). Hence, sport participation risks in youth can be mitigated.

The optimal exercise type and quantity for young agility dogs is unknown, but exercise in general is essential for musculoskeletal development. Opportunities for diverse physical activities might improve development of motor skills. High-intensity training, especially in high volumes or with insufficient preparation, may be harmful. Methods such as neuromuscular training could also help prevent injuries in young canines. Further research is needed to set exercise and training guidelines for young agility dogs.

5.1.2 Training and competing in adult agility dogs

The agility dogs in our sample trained agility for 5–20 minutes once or twice a week. The training frequency appears lower than previously reported: over 70% of North American dogs trained more than once a week (Cullen et al., 2013b) compared to 50% in our Finnish sample, and the reported median frequency of 2.5 training sessions per week is higher than in our study (Dinallo et al., 2017). The session duration was also shorter in Finnish dogs than in over 40% of North American agility dogs who trained for 30-60 minutes at a time (Jimenez et al., 2022), while only a few Finnish dogs trained for half an hour or more at a time. The lack of a standardised definition for training time limits comparison between studies. We included only active training time in the agility field, but it is unclear if other studies also included waiting time or warm-up in their reported times.

The median competition frequency of two runs per month in our results suggests around eight competition days per year, because Finnish dogs, anecdotally, often compete three runs per day. This is lower than the 10–20 trials per year typically reported for North American agility dogs, where each trial usually includes two competition days (Dinallo et al., 2017; Evanow et al., 2021; Jimenez et al., 2022;

Pechette Markley et al., 2022; Sellon & Marcellin-Little, 2022). Overall, it appears that the Finnish dogs in our sample trained and competed less than the North American dogs. This may reflect regional variations in the sport practices or in access to training facilities, or our survey may have reached more handlers who participate less intensively than others.

The more advanced dogs in our sample, interestingly, trained less than beginner dogs. Those dogs who had already achieved a high level in competitions may already have mastered the required skills. The competition frequency also increased with the increase in competition-level. Thus, some of the training time was exchanged for competing. These results are in line with a previous study by Dinallo et al. (2017) from a North American sample, suggesting this trend is international. Thus, in the high-level dogs, the sport-specific loads associated with training seem to be lower, but loads from competing are higher than in dogs at lower levels.

5.1.2.1 Bar heights in agility

The bar heights used in training have, to our knowledge, not been reported previously. Our sample showed that 86% of dogs are trained on jumps that are lower than the maximum bar height used in competitions. For example, in large dogs (wither height ≥50cm), the bar height in training was typically 90–100% of wither height, and the maximum competition height is 105–115% of wither height. This suggests that handlers aim to decrease loads associated with jumping during training. Training bar heights reflected the competition bar heights so that taller dogs jumped higher relative jumps heights both in training and competitions in Finland.

In Finland, there is a 10cm range for bar heights in each height category. Anecdotally, a lower range is used in class 1 (lowest class) and an upper range often in class 3 (highest class). Possibly for this reason, the dogs in the lower classes used lower training bar heights than the dogs in the higher levels. This might be a good practice, because beginner dogs appear to have a lower ability to synchronise limb placements at take-off (Söhnel et al., 2020), and greater limb synchrony was observed in our study with increasing bar height. Thus, beginner dogs might not be as capable of coordinating jump take-off to higher bar heights as are more experienced dogs.

5.1.2.2 Sport surfaces in agility

In North American studies, natural grass is the most-used agility surface (Jimenez et al., 2022; Pechette Markley et al., 2022), whereas it was rarely used in our Finnish sample – likely due to the climate and the lack of such a surface for over half of the

year. Dirt, sand and an artificial turf surface appear common worldwide (Jimenez et al., 2022; Pechette Markley et al., 2022). In Finland, turf with rubber filling was most popular, followed by no infill, cork infill and sand infill. However, discussions about future surfaces have begun with the upcoming European Union ban on rubber infill (Zuccaro et al., 2024). Alternate infills are being developed for human sports with the infills affecting surface properties (Dickson, Sorochan, and Strunk 2020). It remains unknown whether the alternatives are suitable for agility dogs.

Besides our study, one study on agility dogs has related injury occurrence to the popularity of each surface, with the highest incidence of injuries on rubber mat (Jimenez et al. 2022). Rubber mat was not evaluated in our study due to being so rare in Finland, but none of the other surfaces were among the main risk factors, suggesting that they were not important predictors of injury in our sample. Thus, further research is required on the effect of surfaces on injury risk and performance in agility.

The variation of surface properties in the same agility field or arena could also affect injury risk. In greyhounds, injuries appear to occur commonly in sections of the track where fluctuation in the surface properties is high between the inside and middle of the track (Hayati et al. 2020). Surface irregularity could contribute to the injuries, highlighting the role of maintenance practices of sporting surfaces for safety.

5.1.3 Warm-up of agility dogs

Nearly all dogs in our study were always warmed up before performing agility, consistent with previous studies (Cullen et al. 2013b; Essner et al. 2022; Kerr, Fields, et al. 2014). Frequency, length or content of the warm-up was not linked to injury risk in our study. We were possibly unable to measure the key aspects of warm-up that would protect from injuries.

The warm-up consisted only of walking and/or trotting for every tenth dog in our sample. Evidence from human sports shows that neuromuscular warm-up programs, which include aerobic and plyometric jumping exercises as well as strength and balance training, reduce injuries more effectively than the 'usual warm-ups' (Ding et al. 2022; Herman et al. 2012; Thorborg et al. 2017). Thus, the non-specific warm-up of some agility dogs, consisting only of aerobic exercise, may not offer all the benefits that a more complete warm-up program could offer. Tricks and/or play were involved in warm-up for many dogs in our study as well as in Sweden (Essner et al. 2022). The warm-up tricks could include strength or balance exercises, but further research is required to evaluate details of warm-up routines. Additionally, research is needed to study the effect of warm-up in agility dogs and to develop effective warm-up programs aimed at injury prevention.

5.1.4 Musculoskeletal care

Providing musculoskeletal care, such as massage, for agility dogs appears to be a common practice both in North America and in our Finnish sample (Cullen et al., 2013b; Kerr, Fields, et al., 2014). In our study, over 60% of the agility dogs were treated by a massage therapist, physiotherapist or other professional at least four times a year, which provides regular check-ups for these dogs. Dogs competing at higher levels were more likely to receive regular musculoskeletal care. These dogs possibly require preventative interventions more often, or the owners of these dogs provide this care hoping to reduce injuries or improve performance.

The professionals used varied regionally: massage therapists and physiotherapists were visited most often in Finland, whereas chiropractors were the most frequently consulted service provider in North America (Kerr, Fields, et al., 2014). The treatment modalities used by different professionals are likely to vary, which could influence the effects of care. The availability of professionals is probably affected by the educational opportunities and legislation in different regions.

No evidence exists that providing musculoskeletal care reduces risk of injuries. In fact, dogs receiving such treatments have had increased odds of injury (Cullen et al., 2013b; Kerr, Fields, et al., 2014). This was suspected to be due to reverse causality, meaning that this care was provided after injuries. Our survey found that regular physiotherapist visits prior to injuries were a risk factor, though the reason for this is unclear. The statistical model was adjusted for prior injuries, suggesting that physiotherapy was a risk factor independent of them. Owners taking their dogs to physiotherapy regularly might be more observant of subtle clinical signs or more likely to rest their dogs in case of minor clinical signs, increasing the likelihood of the dog to be classified as injured. This highlights the need for future prospective studies with independent injury assessments by veterinarians.

5.1.5 Physical exercise and conditioning

The physical activity of Finnish agility dogs in our study differs somewhat from previous studies on North American dogs: the lower competition and training frequencies of the Finnish dogs previously mentioned are accompanied by greater walking duration and a somewhat lower frequency of conditioning exercises (Cullen et al., 2013b; Kerr, Fields, et al., 2014; Sellon & Marcellin-Little, 2022). This is further discussed next.

5.1.5.1 Dog walking and other dog sports

Walks with the owner provide some basis for aerobic fitness. Dogs in Nordic countries have regular long walks; with Finnish dogs in our study were typically walked for 1.5 hours per day, similar to Swedish agility dogs (Essner et al. 2022). Dog walking amounts are markedly lower in the North American agility dog samples (Kerr, Fields, et al., 2014; Sellon & Marcellin-Little, 2022). The aerobic fitness of agility dogs in Nordic countries might therefore be better compared to the North American dogs. The dog-owner relationship, accessibility to walking areas and the perceived exercise requirements of the dog influence dog walking habits along with other factors (Westgarth, Christley, and Christian 2014). Variations in the physical environments and cultural differences in perceived exercise requirements could explain differences in dog walking habits between agility dog owners in North America and Nordic countries. It is unknown what other exercise opportunities these dogs have, such as time spent free in yards and how this affects their total physical activity. Aerobic fitness in humans improves recovery from high-intensity exercise (Tomlin & Wenger, 2001) and reduces the odds of injury (Lisman et al. 2017; McDonald, Witchalls, and Newman 2017). Further research is required to evaluate aerobic capacity and other aspects of physical fitness in agility dogs as well as associations with performance and injury risk.

The duration of daily walks was neither a protective nor a risk factor for injury in our study. Participation in other physically demanding sports (e.g., canicross, herding, hunting) was a protective factor in our results, potentially due to additional physical conditioning, which could reduce injury risk. These activities also offer the variability recommended for young human athletes (Carder et al. 2020). Ensuring a variety of physical activities could enhance agility dogs' welfare by possible reductions in injury risk. However, these recommendations cannot be based on our study alone.

5.1.5.2 Conditioning exercises

Three-quarters of the agility dogs in our sample performed conditioning exercises to improve strength, speed, endurance, and/or body control, like in the North American and Swedish samples (Cullen et al., 2013b; Essner, Hesbach, et al., 2022; Sellon & Marcellin-Little, 2022). However, only 18% of Finnish agility dogs in our sample performed these exercises at least twice weekly and half only occasionally (not even every second week). The frequencies appear lower than in the earlier North American sample (Sellon and Marcellin-Little, 2022). Exercises in neuromuscular training programs for injury prevention in humans are performed two or three times a week (Taylor et al. 2015; Thorborg et al. 2017), with compliance affecting the protective effect (van Reijen et al. 2016). The frequencies of the conditioning exercises were low in our agility dog sample, so performance

enhancement and injury reduction are unlikely. Scientific evidence suggests that weekly core exercises may reduce risk of cranial cruciate ligament rupture in agility dogs (Sellon and Marcellin-Little, 2022). The conditioning exercises did not reduce odds of injury in our sample, possibly due to the low frequency and due to owners designing the programs on their own without professional involvement.

A physical fitness assessment and a development program comprising progressive exercises has been proposed for working dogs (Farr et al., 2020). The reliability of only one of the assessment tools, the Penn Vet Working Dog Center Sprint Test, has been researched (Farr et al., 2023). Other tools and the effects of this exercise program on performance or injury prevention are yet to be evaluated. The program does not include tools for assessing aerobic fitness; however, a separate field test has been proposed for this purpose in dogs (Söderlund et al., 2023). The exercise program and some of the proposed assessment tools may also prove useful for agility dogs – possibly with some modifications. Alternatively, and probably preferably, exercise programs specific to agility dogs could be developed and tested.

5.2 Jumping at speed

The amount of agility training and competing provides some information on the loads of the sport, but the actual sport performances details, such as jumping biomechanics, offer a more complete understanding. Approximately 65% of the obstacles are bar jumps in a competition course (Cullen et al. 2013a). Thus, on a 20-obstacle course, there will be an estimated 13 bar jumps, which cumulate in 39–52 bar jumps per competition day, using the reported typical number of runs/day (Pechette Markley et al. 2022). Thus, knowledge of the loads associated with jumping and the factors affecting them is crucial to understanding the demands of the sport.

5.2.1 Speed in agility

Agility, although submaximal, is known as a fast-paced sport: in our sample, the median of average speed of a faultless competition course was 4.3 m/s with greater speeds in taller dogs and in more advanced competition levels. Average speeds of 4.5 m/s to 5.8 m/s have been reported in large agility competitions in the United States (Pechette Markley et al. 2024), possibly including mainly high-level agility dogs. Maximum speeds during an agility remain unknown, but a mean velocity up to 8 m/s has been reported in a straight-line jump sequence (Pfau et al. 2011), which is still below the speed of dogs galloping on a flat in non-greyhound breeds (Walter and Carrier, 2007). This is because jumping reduces the dogs' velocity on an agility course: horizontal velocity was lower at higher bar heights in our study with an

estimated difference of 0.4 to 0.7 m/s at take-off between 80% and 120% bar heights. The speeds are likely to be increased at even lower bar heights. Velocity was decreased already at the approach to the second jump, suggesting that dogs were unable or unwilling to regain their speed during the six-meter distance between jumps.

Greater speed could increase the injury risk by introducing a higher risk of errors for both the handler and the dog, potentially leading to falls, collisions, or slipping. Speed is a major determinant of kinetic energy: when speed doubles, kinetic energy quadruples. Increased kinetic energy at higher speeds could raise the risk of tissue damage during a collision or fall, where the dog's mass is sometimes abruptly stopped. Speed has been suggested as the cause for a higher risk of injuries in Border Collies (Cullen et al. 2013b; Pechette Markley et al. 2021). Higher speed has indeed been shown to increase the odds of injury in flyball dogs (Blake et al. 2023; Pinto et al. 2021). Our study was the first to investigate the association between speed and injury in agility dogs. Speed was not included in the multivariate model, suggesting that other variables were better predictors of injury in our sample. The measure of speed could have been inaccurate: the average speed of faultless runs could have been affected by factors such as handler skills and the course. This potential inaccuracy could have resulted in a failure to identify speed as a risk factor. Thus, further research is required to evaluate the association of injury and speed in agility.

Besides low bar heights, longer distances between jumps increase the speed on a straight-line jump sequence (Birch et al. 2015a, 2015b). Anecdotally, obstacle distances, as well as speeds, have increased over the recent years, with a suspected correlation between the two. A small study of two dogs reported maximum speed after 15 to 20 meters of acceleration (Farr et al., 2023), indicating that extending acceleration opportunities up to 15 meters on an agility course could increase the dogs' speed. Greater maximum speeds could result in greater decelerative forces, because certain parts of the course, such as turning jumps, are performed at lower speeds (Söhnel et al., 2021, 2020). The evidence suggests that cumulative decelerative loads may be associated with overuse injuries in human athletes (Jaspers et al., 2018). Pre-activation of muscles is considered important for deceleration ability (Harper et al., 2022). Poor pre-activation of muscles has also been suggested as the cause of greater limb compression in beginner dogs (Söhnel et al., 2020). Therefore, the ability to decelerate may be poorer in beginner dogs than in more advanced dogs. Further research is required to clarify which are the safest ways to control speed on an agility course.

5.2.2 Take-off to jump and the effect of bar height

Jumping from the relatively high-speed gallop requires a transfer of mainly horizontal movement at the approach into the vertical direction to achieve the required vertical velocity at take-off. Our research shows that bar height not only affects the horizontal velocity but also alters the take-off biomechanics in multiple ways. The height of the dog's jump is determined by the vertical velocity and the height of the trunk at lift-off (Enoka, 2015). Therefore, it was to be expected that the vertical impulses at take-off increase with increasing the bar height. The prolonged stances phases allowed these vertical forces to be produced over a longer duration. Thus, the peak vertical forces were not necessarily increased at take-off to a higher jump. Our study could not, unfortunately, evaluate the peak forces or the impulses of individual limbs but only the actions of limb pairs. Nevertheless, prolonging the stance phases may be a strategy to limit an increase in the peak forces, or longer stance times may be the result of lower velocity.

The greater synchrony of limbs allowed the vertical forces to be produced over a relatively short period, causing a rapid increase in vertical acceleration during the take-off. Interestingly, the bar height did not affect the weight distribution, which was measured as the distribution of total vertical impulse between the fore- and hindlimbs. Thus, both limb pairs contributed to the increase in the vertical impulse. The vertical forces produced by the forelimbs cause a nose-up rotation of the trunk because the forelimb paws are positioned in front of the centre of mass, which in our study resulted in a steeper trunk angle at the lift-off at higher bar heights. Dogs took off into the aerial phase at a steeper angle at the highest bar height with shorter take-off distances, which suggests that the form of the trajectory during the aerial phase is affected by the bar height, although this study could not measure it.

In a previous study, the length of the jump increased up to bar heights of 125% of wither height, whereafter they started to decrease again (Birch et al. 2016). It might be that at high bar heights (120% of wither height and beyond), the dogs prioritised vertical force production over the horizontal one to produce the trajectory with the lowest mechanical energy (Daniels & Burn, 2018). Our results show more decelerative net cranio-caudal impulses at higher bar heights, which could be due to greater deceleration, lower acceleration, or both from each limb. However, since our study could not measure the forces from individual limbs, we cannot determine specific contribution of each limb. These altered cranio-caudal impulses decreased the horizontal velocity during take-off to the highest bar height, whereas at lower bar heights the dogs kept accelerating during take-off.

Joint kinematics at take-off had been very sparsely studied in agility dogs prior to our work. For many of the measured joints in our study, the range of motion (ROM) increased at 120% of the wither height to bar height compared to the lower bar heights, although the absolute differences in joint angle values were often small at 2 to 4 degrees estimated difference. Bar height affected joint kinematics mainly

in the trailing forelimb and in both hindlimbs, suggesting that these limbs have key roles at increasing height of a jump performance. Further details are discussed next.

5.2.2.1 Joint kinematics in forelimbs

The trailing forelimb produced 30% of the vertical impulse at take-off to the bar jump in agility dogs in a previous study – a higher proportion than any other limb (Söhnel et al., 2020). The trailing forelimb could have contributed to the increase of the forelimb vertical impulse more than to the leading forelimb in our study. The trailing forelimb is also more compressive at take-off to an agility jump because of reduced limb stiffness (Söhnel et al., 2020). Our work could not evaluate limb stiffness, but the forces might have increased more in the trailing forelimb, resulting in greater limb compression. The greater elbow peak flexion and carpal peak extension observed in our study could indicate increased limb compression in the trailing forelimb.

The peak extension angles of carpal joints are similar to the angles reported at the A-frame and landing from a jump (Castilla et al., 2020) but are less than reported at first contact to the A-frame (Appelgrein et al., 2018). Carpal extension is more pronounced during agility activities than in a trot (Allen et al., 1994; Brady et al., 2013; Jarvis et al., 2013). In a gallop, carpal extension angles as high as during jumping have been reported for only one breed (Akita) out of 32 breeds (Fischer and Lilje, 2014a). Carpal hyperextension injuries have been reported in agility dogs (Pechette Markley et al., 2021). It is unknown whether the three-degree difference in peak extension between bar heights, observed in both forelimbs in our study, affects the risk for hyperextension injuries.

The shapes of the shoulder angle curves during take-off are intriguing: the trailing forelimb shoulder is most flexed just before the mid-stance, whereas the leading forelimb shoulder peak flexion occurs at the end of stance. This may again reflect the difference in limb stiffness between the trailing and leading forelimbs, which leads to greater limb compression in the trailing forelimb (Söhnel et al., 2020). Looking at the joint angle curves in our results, it seems that much of that difference in limb compression between the forelimbs at take-off may come from the shoulder joint, which is the most injury-prone joint in agility dogs (Cullen et al., 2013a; Pechette Markley et al., 2021). We reported shoulder peak flexion values of around 115 degrees, which occurred just before the mid-stance. Our values appear lower than previously reported for the mid-stance in most breeds during walk, trot and gallop (often 130° or greater) (Fischer and Lilje, 2014a). The joint angle may affect the ability of the stabilising structures to support the joint, because these structures might be adapted to support the shoulder joint at the more extended angles occurring during the gait. The more flexed angles during the jump take-off, with the concurrent requirement to withstand ground reaction forces, might result

in suboptimal support of the shoulder or an unusual strain on the stabilising structures and possibly contribute to the shoulder injuries in agility dogs.

5.2.2.2 Joint kinematics in hindlimbs

Besides carpus, the peak extension values of the hip joint (close to 170 degrees) at take-off were beyond those generally reported during trot and gallop (Allen et al., 1994; Fischer et al., 2018; Fischer and Lilje, 2014a; Jarvis et al., 2013). Hip peak extension angles at jump take-off were also greater than during the stair ascent (Souza et al., 2019). This peak extension occurred at the end of the stance phase when the ground reaction forces are very low as the paw is about to leave the ground (Söhnel et al., 2020). The hip extension is going to stretch the hip flexor, *m. iliopsoas*, which is among the most injured structures in agility dogs (Evanow et al., 2021; Pechette Markley et al., 2021). During a vertical jump from a standing position, where the hindlimb action resembles that of agility jumping *m. iliopsoas* is activated until the end of stance phase (Tokuriki, 1979). Therefore, *m. iliopsoas* could be working eccentrically during the jump take-off, controlling the extension of the lumbosacral spine and hip joint. Eccentric muscle actions can result in muscle damage, especially with an increasing muscle stretch (Allen, 2001). Thus, repeated jump take-offs could contribute to chronic iliopsoas injuries because the *m. iliopsoas* stretch might be excessive; these injuries are thought to result from repetitive microtrauma (Kieves, 2020). Reducing the bar height might not mitigate this risk: the peak hip extension angles in our study appeared to be greater in the trailing hindlimb and unaltered by the bar height in that limb. However, almost three thirds of agility dogs with iliopsoas injury have a concurrent musculoskeletal condition, such as cranial cruciate ligament instability, lumbosacral pathology or hip pathology (Sack et al., 2023). Only one-fourth might be primary iliopsoas injuries (Sack et al., 2023). Thus, jumping alone might not be responsible for most iliopsoas injuries, but those other pathologies could increase the need to control the lumbosacral and hip extension during jump take-off, increasing the load on the iliopsoas muscle.

Tarsal peak flexion increased in both hindlimbs when the bar height was at 120% of the wither height compared to lower bar heights. Range of motion (ROM)and peak flexion increase in greyhounds with increasing horizontal acceleration on the flat (Williams et al., 2009). Jumping over an obstacle requires acceleration of vertical velocity at take-off. Agility dogs may utilise a strategy similar to increase vertical acceleration as greyhounds on the flat while increasing horizontal acceleration. Stretching the extensor muscles of the tarsus before contracting them may have resulted in the muscles performing more positive work and producing greater power (Enoka, 2015). One proposed mechanism for the benefits of a stretch-shortened cycle is storage and release of elastic energy (Enoka, 2015). Indeed,

extensors of the tarsal joint, *m. flexor digitorum superficialis* and *m. gastrocnemius*, appear to be specialised for elastic energy storage – at least in the greyhound (Williams et al., 2008). Thus, agility dogs may be using elastic energy to increase jump height. Tarsal injuries are very rarely reported in agility dogs (Essner et al., 2024; Pechette Markley et al., 2021; Sellon et al., 2023), suggesting that tarsal flexion at take-off is unlikely to have a significant impact on the overall injury rates of agility dogs.

5.2.3 Navigating obstacle sequences

Obstacles are performed in sequence on an agility course, where the previous and the following obstacle affect the approach and exit from each obstacle. We used a sequence of three jumps with a six-meter distance between two jumps to measure the effect of the bar height in a sport-specific setting. The distance between the obstacles restricts the approach options each dog can choose from: e.g., in our set-up, the dogs took either one or two strides between the first and second obstacle. Thus, agility dogs need to adjust their movement, not only regarding the bar height but also considering other aspects of the obstacle sequence.

For some variables, the mean differences were larger between the different approach stride numbers than between the different bar heights. For example, with a one-stride approach, dogs took off over 70 cm farther from the jump than with a two-stride approach, while mean differences between bar heights were up to 9 cm. Interestingly, the calculated height of the jump was greater with the one-stride approach due to the greater vertical impulses, suggesting that the dogs jumped higher than was necessary by the height of the obstacle. The apex of the jump trajectory might have been before the obstacle (on the take-off side) with a one-stride approach, requiring a higher jump. Dogs aim to minimise mechanical energy by having the apex further in front of the obstacle when take-off distance is increased by ground bars (Daniels & Burn, 2018). Some dogs in our study likely preferred jumping from further away rather than decelerating to fit in another stride. It is unknown why each dog chose the striding they used or why some dogs varied the number of approach strides. These results highlight the complexity of agility course performances. We can easily regulate the bar height, but we must bear in mind that multiple other factors influence the physical loads associated with jumping in a course setting.

5.3 Injuries in agility dogs

Sport-related injuries are a welfare concern in agility dogs. A third of agility dogs in our survey had suffered an agility-related injury at some point during their career. The proportion is similar to two previous surveys evaluating agility-related injuries

(28–32%) (Cullen et al., 2013a; Evanow et al., 2021) and somewhat lower than in a recent study with a smaller sample (45%) (Jimenez et al., 2022). However, direct comparisons between the studies might be misleading due to lack of standardised injury definitions and the dogs' varying career durations at the time of survey participation. Additionally, none of the studies have had a random sample: the owners of the injured dogs might have been overrepresented.

Ideally, injuries should be related to measures of exposure, such as hours spent training, to calculate the injury rate (injuries/exposure) (van Mechelen et al., 1992). The estimated rate of the competition-related injuries in our study was 1.44 injuries / 1000 competition runs. This is slightly lower than the 1.72 injuries / 1000 runs reported for agility dogs by Kerr et al. (2014) and markedly lower than the reported rates of 19-34 injuries / 1000 race starts in racing greyhounds (Palmer et al., 2021; Sicard et al., 1999). Thus, the welfare concerns regarding sport-related injuries might not be as serious in agility dogs as in greyhounds.

The rate of training-related injuries could not be estimated in our study, because the training hours for the whole year were unavailable for all dogs. However, the time spent training and competing appears to be less for Finnish dogs compared to those in the North American studies. No indication exists that the proportion of injured dogs would be lower in Scandinavian or Finnish agility dogs (Cullen et al., 2013a; Evanow et al., 2021; Inkilä et al., 2022b; Pechette Markley et al., 2021), possibly suggesting a higher rate of injuries per exposure hours in Finnish agility dogs.

Future studies of agility dogs should measure injury rates instead of incidence, because that allows for a more detailed comparison of risk between both dogs and between studies (van Mechelen et al., 1992). The exposure related to training could be most accurately measured with objective measures (e.g., accelerometer-based devices) or at least prospectively with questionnaires.

5.3.1 Defining injury

Studies of agility dog injuries often rely on owner surveys (e.g., Cullen et al., 2013b, 2013a; Evanow et al., 2021; Pechette Markley et al., 2021, 2022). Some surveys, including ours, use a time-loss definition for injuries (e.g., a certain time lost from training) (Levy et al., 2009; Pechette Markley et al., 2021), like the surveillance systems used in human sports (Ekegren et al., 2016). However, some studies lack a clear injury definition (Cullen et al., 2013a; Evanow et al., 2021; Jimenez et al., 2022). Owner definitions of 'injury' could vary widely: one study included injuries to all body systems, including, for example, digestive and ophthalmologic injuries (Essner et al., 2024), whereas other surveys of agility dogs' injuries appear to focus mainly on musculoskeletal injuries (Cullen et al., 2013a; Evanow et al., 2021; Pechette Markley et al., 2021).

Certain owners may be more aware of injury risk, note more subtle clinical signs, more readily define subtle signs of injury, or be more likely to rest their dog if concerned about injury. Thus, factors related to the owner, rather than to the dog, could affect the categorisation of dogs into injured and non-injured. This might explain our finding that the dogs regularly visiting a physiotherapist before their injury had increased odds of injury: injury-aware owners could be those taking their dogs to be treated regularly. Despite the challenges, a standardised injury definition would allow for an improved comparison between agility dog studies.

Alternative study designs would allow injuries to be evaluated independent of the owners: Musculoskeletal abnormalities in working farm dogs have been investigated through regular physical examinations in a longitudinal study (Isaksen et al., 2020). This could be applied to agility dogs, possibly combined with diagnostic imaging or objective gait analysis. The structures most affected by the loads of agility could be revealed if non-agility dogs were also included. Biomechanical studies could then be used to investigate which aspects of the performance load onto these tissues and how those loads could be mitigated.

5.3.1.1 Relationship between injury and agility

Our study included only injuries that owners considered to have resulted from agility, as have some of the previous survey studies (Cullen et al., 2013a; Evanow et al., 2021; Jimenez et al., 2022; Levy et al., 2009). Other studies have evaluated injuries in agility dogs irrespective of the perceived cause (Essner et al., 2024; Kieves et al., 2024; Pechette Markley et al., 2021; Sellon et al., 2018; Sellon & Marcellin-Little, 2022). Surveillance systems for injuries in human athletes include injuries that occur only during competing or training (Alonso et al., 2009; Brooks et al., 2005; Hägglund et al., 2005; Kerr, Dompier, et al., 2014). Both acute injuries, defined as injuries resulting from a single identifiable incident, and overuse injuries, resulting from repeated microtrauma without an identifiable inciting event, are generally included in human studies (Alonso et al., 2009; Fuller et al., 2006; Hägglund et al., 2005). Acute injuries can probably be detected relatively easily in dogs if obvious clinical signs are present directly after the incident. The detection of overuse injuries and milder acute injuries is more challenging. One could still assume that if performing in agility contributes to an injury, some at least mild clinical signs would be observed after agility.

Including all injuries, regardless of their sperceived cause, leads to studying conditions that may not be related to agility. Detection of risk factors could fail if the sample includes a marked number of injuries with no relationship to agility. However, inclusion of all injuries and illnesses gives an overview of the welfare issues related to health in agility dogs, but they should be compared to non-agility dogs to estimate the effects of the sport.

Some of the relatively commonly reported diagnoses in agility dogs, such as torn nail, cranial cruciate rupture, and intervertebral disc disease (Pechette Markley et al., 2021), are also among the common diagnoses in the general dog populations (Forsyth et al., 2023; Pechette Markley et al., 2021). Thus, agility might not affect their occurrence; nevertheless, iliopsoas strain, biceps tendinopathy and medial shoulder syndrome are among the most common orthopaedic conditions in agility dogs (Pechette Markley et al., 2022) but are not commonly diagnosed in the general dog populations (Forsyth et al., 2023; O'Neill et al., 2014). It is unknown whether these are truly overrepresented in agility dogs, suggesting that these tissues are affected by the sport, or if the required diagnostics (e.g., musculoskeletal ultrasound) are performed more often on agility dogs.

5.3.2 Incidents related to injuries

In case of acute injury, a specific incident can be identified as the cause. The owners in our sample reported over half of the injuries to be related to obstacle performance. Previous studies have reported that 32–64% of injuries are obstacle-related (Jimenez et al., 2022; Kerr, Fields, et al., 2014; Levy et al., 2009). However, over 60% of the injuries in our study were first noted after an agility session, not during it. This suggests that, at times, the owners assumed that the incident was the cause of the injury, although the first clinical signs were observed later. A risk exists that some of these assumptions are inaccurate.

However, this might suggest that noticing injuries in the heat of the performance is difficult because exercise and stress reduce pain (Butler & Finn, 2009; Koltyn, 2000; Pacheco-Barrios et al., 2020). Thus, the first clinical signs of injury may appear a while after the agility session. From an animal welfare perspective, discontinuation of an agility session could be encouraged after incidents, such as collision or falls from an obstacle, that may have resulted in tissue damage.

5.3.2.1 Collisions with jump obstacles

Obstacle-related injuries were frequently reported on bar jumps in our sample, consistent with previous reports (Cullen et al., 2013a; Jimenez et al., 2022). This is likely due to the high exposure to bar jumps, the most frequent obstacle on an agility course (Cullen et al., 2013a). Injuries resulting from collisions with obstacles occurred most often on jumping obstacles (bar jump, spread jump, etc.) in our study. Colliding with an obstacle, especially a heavy one, can result in an abrupt halt of the dog. The kinetic energy does not vanish in that case but changes form – possibly to a deformation of the dog's tissues. Dogs with greater weight and velocity could be at a higher risk of injury after a collision due to the greater kinetic energy. Based on our results, collision is one potential injury mechanism in agility dogs.

The collisions occur, anecdotally, during the aerial phase of the jump. The trajectory of the dog's centre of mass during the aerial phase is determined by the take-off. Therefore, a well-executed take-off is crucial for avoiding collisions. Further investigations into the factors associated with collisions are needed to develop preventative measures. Observational studies could be undertaken to evaluate whether the approach and exit angles, the speed at the approach, previous obstacles, colour of the jump, the bar height, or the handling affect the risk of collision. Jumping problems, possibly leading to collisions, are more common in agility dogs with visual deficits such as myopia (Day et al., 2018). Other dog-related factors, such as breed, speed, and personality, may also influence the risk of collision.

5.3.2.2 Injuries associated with dogwalk and A-frame

Besides the bar jump, the dogwalk and A-frame have been commonly associated with injuries in previous studies (Cullen et al., 2013a; Levy et al., 2009) and in our study population. Over 70% of the dogs with a dogwalk-associated injury fell from the obstacle – another potential mechanism for injury in agility. It has been debated whether the currently 30 cm wide obstacle should be made wider, which would increase the margin for error in paw placement. Which factors are associated with falls from the dogwalk is yet to be investigated: dog size, speed and approach angle could play a role.

In our sample, all dogs with A-frame-related injuries used the running contact technique, which involves no deceleration or stopping on the obstacle. The sample was too small for statistical analysis: less than two-thirds of the dogs used this technique overall, suggesting a potential higher risk of acute injuries. Conversely, digit injuries have been reported more frequently in dogs that stop at the end of the A-frame (Sellon et al., 2018). When considering all injuries in our sample, the injury odds were similar between stopped and running techniques, while dogs using other techniques, likely involving deceleration without stopping, had a lower injury risk. This association has, however, not been found in another study (Pechette Markley et al., 2022). Our study could not evaluate whether the 'in between running and stopped' technique truly was leading to lower injury risk or if these dogs had other, unknown protective factors. Different performance techniques may carry different risks: they might load different tissues, or one might be associated with a higher risk of acute injuries but not necessarily overuse.

5.3.2.3 Slipping-related injuries

In two studies, slipping and loss of footing has been reported for 5–18% of injuries (Cullen et al., 2013a; Levy et al., 2009), with slipping being the most common non-

contact cause of injury (Levy et al., 2009). In a more recent survey, owners rated a third of injuries as 'definitely related' to the surface (Jimenez et al., 2022). Details were lacking, but it is likely that at least some of them included slipping. In a third of injuries in our sample, the dog had slipped during an incident that the owner perceived as the cause of the injury. There was no difference in the surfaces across the slipping and non-slipping injuries. Slipping appears to be one relatively common injury mechanism in agility dogs, which could be further evaluated using video analysis of slipping incidents that resulted in an injury.

Interestingly, the odds of slipping-related injuries in our sample were greater on surface types that were less familiar to the dog (not performing agility weekly). This suggests that the familiarity of the surface could be important and that dogs adjust their performance to each surface. Dogs performing on a larger variety of surfaces have been reported to have a greater number of performance deficits on some of the common surfaces (Jimenez et al., 2022). Constant adjustment to new surfaces possibly reduces a dog's capability to perform. It might be beneficial to train on a smaller number of different kinds of surfaces as a preventative measure and, in the case of new surfaces, allow the dog to adjust before competing on that new surface. Future studies could evaluate how surface familiarity affects performance and safety in agility and what exposure results in adaptation with a low risk of slipping incidents. Additionally, course planning is likely to affect the risk of slipping, because friction is challenged when horizontal forces along the surface, such as turning or deceleration, are greatest.

Fatigue is another factor that could influence the occurrence of slipping, falling and collisions. Injuries in our sample typically occurred towards the end of the training session or on the later courses of a competition day. This suggests that fatigue of the dog or the handler could influence the risk of injury. In human athletes, postural control and muscle strength decrease when fatigued, which in turn can increase injury risk (Verschueren et al., 2019). This highlights the need for proper conditioning for the demands of the sport. Additionally, handlers should be instructed to observe their dogs for the signs of fatigue, such as excessive panting, muscle trembling, and gait changes (McCauley & Dyke, 2018). Studying the occurrence of slipping, collisions, and falls during longer training sessions or competition days could reveal associations between fatigue and risk of these incidents.

5.3.3 Description of the injury

The results regarding the anatomical locations of injuries should be evaluated with caution, because in all studies, including ours, veterinary records have not been used to confirm the reports (Cullen et al., 2013a; Evanow et al., 2021; Pechette Markley et al., 2021). Injuries to the back and shoulder/scapular regions were

common in our studied dogs in line with previous studies, (Cullen et al., 2013a; Essner et al., 2024; Evanow et al., 2021; Jimenez et al., 2022; Levy et al., 2009; Pechette Markley et al., 2021; Sellon et al., 2023). These anatomical sites appear to be susceptible to injuries in agility dogs. It is currently unknown whether injuries to these sites occur at a higher prevalence in agility dogs compared to non-agility dogs.

In contrast to previous studies, the injuries to the groin region were seldomly reported in our study (Evanow et al., 2021; Jimenez et al., 2022; Pechette Markley et al., 2021). It seems that diagnoses of iliopsoas injuries might be rarer in Finland compared to the mainly North American samples. This may be due to true differences or to variations in diagnostics.

Veterinary care due to the agility-related injuries was sought less often in our sample, compared to earlier studies (Cullen et al., 2013a; Levy et al., 2009). Based on recovery times, the injuries were not necessarily less severe (Cullen et al., 2013a; Levy et al., 2009), suggesting that Finnish agility dog owners were less likely to seek veterinary care for some reasons other than the injury's severity. Over 10% of injured agility dogs in our study were retired due to the injury, with previous studies reporting injury-related retirement values from 6%–12% (Evanow et al., 2021; Levy et al., 2009). Injuries this severe could also have long-term implications for a dog's everyday life and therefore negatively affect welfare of the dog.

5.3.4 Risk factors for injuries

Our study revealed several risk or protective factors that had not been reported previously. Two of the identified risk factors, i.e., previous agility-related injuries (Cullen et al., 2013b) and use of regular physiotherapy (Cullen et al., 2013b; Kerr, Fields, et al., 2014), were in line with previous studies. The identified risk factors always depend on the questions of the survey and the studied sample. Selected factors that have not been covered yet are discussed next.

5.3.4.1 Previous injury as a risk factor

Two or more previous agility-related injuries were found to be the most important risk factors for an agility-related injury during a full calendar year in our study. However, only one previous injury did not significantly increase the odds of another injury. A previous injury was also found to be a major risk factor in a previous study (Cullen et al., 2013b), but the number of previous injuries was not evaluated.

In human athletes, a previous injury is known to increase the risk of a recurrence of the same injury or of subsequent injuries in a different anatomical location or type (Fulton et al., 2014; Green et al., 2020; Toohey et al., 2017). Human studies show decreased strength and proprioceptive deficits (e.g., altered static and

dynamic stability) after lower limb injuries (M. S. Andrade et al., 2002; Bonfim et al., 2003; Bressel et al., 2004; O'Sullivan et al., 2008). Reduced muscle strength and poorer postural stability are known intrinsic risk factors for various lower limb injuries in humans (Mason et al., 2022; Peterson et al., 2022; Whittaker et al., 2015; Witchalls et al., 2012). Injuries could have similar effects in dogs; thus, the finding of a previous injury as a risk factor is feasible – although one must remember that these studies in agility dogs do not prove causality.

The rehabilitation of a sporting dog aims to restore the function of the body and to allow for a safe return to the sport. It is concerning that only every fifth agility dog in our sample received rehabilitation as part of physiotherapy. In Finland, physiotherapists are professionals specialised in rehabilitating patients after injuries, and they have the knowledge to apply progressive conditioning plans for agility dogs. Therefore, it is unfortunate that although 40% of dogs received physiotherapy, only half of these received structured rehabilitation. Proper rehabilitation of agility dogs after an injury could be crucial in preventing subsequent injuries and, therefore, important for welfare of these animals.

5.3.4.2 Injury-prone Border Collies

Border Collies are reported in multiple survey studies to have increased odds of injury compared to other breeds of agility dogs (Cullen et al., 2013b; Evanow et al., 2021; Fry et al., 2022; Kieves et al., 2024; Sundby et al., 2022). Border Collies were also overrepresented among the injured dogs in our sample. This breed was not, however, included in the final multivariate model, which differs from the previous studies (Cullen et al., 2013b; Evanow et al., 2021; Fry et al., 2022; Kieves et al., 2024; Sundby et al., 2022). Our results suggest that other factors were better predictors of injury in our sample.

The reason for the higher prevalence of agility-related injuries among Border Collies is unknown. Musculoskeletal disorders and chronic lameness are more prevalent in Border Collies compared to cross breeds and other popular breeds in large-scale studies among general dog populations (Forsyth et al., 2023; O'Neill et al., 2014). These samples could also include agility dogs, although it is likely that other factors also influence the higher prevalence of musculoskeletal issues in this breed. Border Collies are probably a popular choice for competitive handlers, because they are known for their speed in agility. Thus, they often compete at higher levels and with competitive handlers, factors that have been linked to a higher injury risk for the dog (Evanow et al., 2021; Pechette Markley et al., 2022; Sellon et al., 2018; Sellon & Marcellin-Little, 2022; Sundby et al., 2022). Additionally, it might be that Border Collies participating in agility train, compete or are cared for differently than other breeds. We might have been able to detect those factors better than previous studies because we surveyed about routines prior to the injury.

Highlighting the multifactorial nature of injury causation, psychosocial factors, such as a history of stressors and personality, are associated with injury risk in human athletes (Slimani et al., 2018; Tranaeus et al., 2015). Personality differences have also been observed between breeds: Border Collies tend to be high-energy dogs with a high training focus (Salonen et al., 2023), and they display a high prevalence of compulsive staring and fly snapping compared to other breeds (Salonen et al., 2020). Personality or behavioural traits have not yet been evaluated as risk factors for injury in agility dogs, but their investigation could provide insight into factors potentially affecting injury risk.

5.3.4.3 Risk factors related to training and competing

Our survey differed from the previous ones in that we evaluated injuries during one specific year and surveyed about training and competition routines prior to the injury. Surveying about routines prior to the injury, although inferior to prospective studies, might be the reason why some new risk factors relating to training and competing were found.

A dog with a moderate competition frequency of 1.5 to < 3 runs per month had the lowest odds of injury in our sample. The higher workloads associated with high competition frequency could possibly increase injury risk. Those competing more frequently might have more competitive owners, and factors indicating competitiveness have been linked with higher injury risk in previous studies (Evanow et al., 2021; Pechette Markley et al., 2022; Sellon et al., 2018; Sellon & Marcellin-Little, 2022; Sundby et al., 2022). However, dogs with low competition frequency might not be properly prepared for the demands of the sport, which could increase their risk for injury. The number of competitions per year has not made it to the multivariate models in previous studies (Evanow et al., 2021; Pechette Markley et al., 2022) – possibly because frequency at the time of injury has differed from those at the time of survey participation.

The temporal relationship might have allowed us to detect an association between training frequency and injury. Agility dogs with more than two training sessions a week had increased odds of injury, whereas the time spent training per week showed no association with injury. Thus, it might be that these dogs were not sufficiently recovered between training sessions due to the higher training frequency.

Further studies are required to evaluate how training and competition loads affect injury risk. The ratio of acute and chronic workload is associated with injury risk in human athletes (R. Andrade et al., 2020; Eckard et al., 2018; Griffin et al., 2019; Maupin et al., 2020). A gradual workload increase can lead to adaptation; thus, the absolute external workload (e.g., training frequency) does not necessarily result in higher injury risk. However, a rapid workload increase may exceed the

adaptive capacity of the body, resulting in an injury. Prospective studies are needed in agility dogs to further investigate how training and competition loads influence injury risk – ideally by incorporating the acute:chronic workload ratio used in human athletes (R. Andrade et al., 2020; Eckard et al., 2018; Griffin et al., 2019; Maupin et al., 2019).

5.4 Limitations

Survey designs have some inherent limitations. As discussed in previous sections, the main concern in studies I and II was that owners defined their dog either as injured or non-injured, which could be affected by factors related to the owner as well as to the dog itself. We aimed to control some of the variation by deriving the injury definition from human injury surveillance research – with the addition of observable clinical signs. We limited most questions to routines and injuries during the past calendar year to decrease the likelihood that owners remember surveyed actions and events inaccurately. The retrospective design still does not provide the same level of detail and accuracy as prospective study designs. Our study could have been affected by recall bias: owners might have generally been able to remember some details (e.g., more dramatic ones) and forget others (Coughlin, 1990).

Social desirability bias may also have affected some answers in the survey: owners could have chosen the answer they considered socially acceptable (Larson, 2019), especially because the survey was not anonymous. Identification was necessary to utilise the competition results database for speed and competition frequency variables. The sample was not random; thus, certain owners (e.g., those of injured dogs) might have been more likely to participate. We reached about 15% of the population of Finnish agility dogs that were estimated to fulfil the criteria of actively training and competing in agility during the evaluated period. We consider this response rate an acceptable but not excellent response rate.

One of the major limitations in study III was the lack of kinetic data from individual limbs. The large-sized force plates placed in a row were not ideal for measurement of the dogs. Measuring the forces individually of each hindlimb, for example, would have required isolating one limb on the force plate at a time, while ensuring that the other hindlimb stepped off the plate because force plates were serial, not parallel. However, this approach would have necessitated a significantly higher number of trials per dog to collect sufficient data, which was beyond the limits set by our ethical approval for trial numbers. The combined data, despite the limitations, offer information on the action of the limb pair, which at this stage of agility research, is still valuable.

Additional challenges in the force plate measurement were encountered, because in some trials the leading forelimb and the trailing hindlimb contacted the same force plate simultaneously, resulting in overlapping force curves. To estimate

impulses produced by fore- and hindlimbs despite the overlap, we used a simple approach of dividing the impulses between the fore- and hindlimbs using the lowest vertical force values, as performed by Pfau et al. (2011). The effects on our analysed results are diminished by inclusion of trials where this overlap was a limited magnitude and by evaluation of potential error at these overlap magnitudes. As mentioned, future studies should aim to have limbs on individual force plates.

Measurement of joint angles using skin markers is always an estimate, because we cannot directly measure the movement of the bones with these devices. The markers move on top of the bony landmarks during the animal's movement due to skin displacement error (Fischer et al., 2018; Kim et al., 2011; Schwencke et al., 2012) – especially in the more proximal joints (Fischer et al., 2018).No means currently exist, unfortunately, to correct this error in dogs. It is unknown whether the error remained constant over the bar heights in our study. If not, it could have affected the estimated differences between the bar heights, which could be relevant because the differences in joint angles between bar heights were often rather small (< 5 degrees). Therefore, the results regarding the shoulder and hip joints should be evaluated with caution. However, many of the largest differences were seen in the more distal joints, carpus and tarsus, and these are more likely to be accurate.

Controlling dogs' speed in study III would have allowed to study the effects of bar height in greater detail – as done in a previous study (Pogue et al., 2022). However, in an agility course dogs can adjust their speed freely, but bar height can be controlled. We wanted to evaluate effect of bar height in a sport specific setup and, therefore, did not aim to control speed of the dog. The biomechanical differences between bar heights in our study could be results of differing speeds, take-off angles and other alterations dog chooses to do in response to the bar height.

5.5 Next steps towards prevention of injuries

In summary, the following suggestions are made to guide agility dog research towards effective injury prevention strategies:

1) Standardised injury surveillance procedures should be established. A common definition of injury is needed. Exposure to agility should be measured to allow calculation of injury rates.
2) Further studies on the prevalence of musculoskeletal disorders in agility dogs compared to non-agility dogs are needed to reveal injuries potentially caused by the agility sport. Diagnostics imaging studies of agility and non-agility dogs of the same age and breed could shed light on which structures and tissues are affected by the sport.
3) Prospective studies are suggested to further investigate the risk and protective factors for injury in agility dogs. A prospective design allows for

better estimation of exposure as well as a more detailed investigation of workload-related factors.

4) Factors related to personality and behavioural traits should be evaluated as potential risk factors for injury.
5) Biomechanical studies are lacking for many of the obstacles, and most have been evaluated only in straight-line sequences. More detailed research on, for example, joint moments would offer further details on the performance of the dogs. These studies would aid in identifying aspects of the agility performance that load the tissues most affected by the injuries.
6) Video analysis of incidents that have been associated with injuries, preferably with veterinary diagnostics, are needed to gain further information on injury mechanisms – especially if high-quality video material is available.
7) Risk factors for the occurrence of the above-mentioned incidents should be identified. These could include factors related to course design as well as dog- or handler-related factors.

Suggestions one to three could be considered as stage 1 (injury surveillance) of the TRIPP framework for injury prevention. Established injury surveillance tools are also needed when the effectiveness of prevention tools is evaluated. The other suggestions relate to stage 2 (injury mechanism) of the TRIPP framework. Injuries in agility dogs are multifactorial with various intrinsic and extrinsic risk factors affecting the susceptibility of an individual dog – some of which could be modified. Findings from both stages 1 and 2, alongside multidisciplinary knowledge of biomechanics, sports medicine, etc., are utilised to develop actual preventative tools (stage 3) such as neuromuscular training programs, alterations of workload, or regulation changes. The further stages include the evaluation of the effectiveness of these tools as well as their application to field settings.

6 Conclusions

1) The survey described training, competition, and management routines in Finnish competition-level agility dogs and revealed the differences across competition levels.

2) Agility dogs were prone to injuries in their forelimbs and back. Injuries were often associated with incidents such as collisions, slipping, or falling, which are proposed as injury mechanisms in agility dogs.

3) Significant risk factors for injury included multiple previous injuries and high training frequency. Moderate competition frequency, A-frame performance technique, and participation in other physically demanding sports were found as protective factors for agility-related injury. These factors could be further investigated in prospective studies.

4) Increasing the bar heights led to biomechanical adaptations in the dogs' jumping performance, including greater vertical impulse and limb synchronisation. The range of motion increased in selected limb joints through greater peak flexion or extension as the bar height increased, which may indicate greater load on tissues.

This research contributes to improving the welfare of agility dogs by expanding the scientific knowledge of physical loads in agility dogs. Its information on the incidence of injuries, risk factors, and potential injury mechanisms serves as a valuable resource for agility handlers, trainers, veterinarians, physiotherapists, and researchers. This knowledge can be utilised when working towards effective injury prevention strategies for agility dogs.

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