

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

A study of debilitating orthopaedic conditions
of working New Zealand Police
German shepherd dogs.

A thesis presented in partial fulfilment of the requirements for a
Doctorate degree in Veterinary Science at Massey University,
Manawatu, New Zealand.

Andrew John Worth
2015

Abstract

This thesis explored the causes of retirement or loss from service of German shepherd Police dogs working in New Zealand. Abnormal development of the hip joint with subsequent development of osteoarthritis (hip dysplasia), and degeneration of the lumbosacral junction, were identified as the leading causes of early retirement of Police dogs due to an inability to meet the physical requirements of Police work.

Hip dysplasia is a multifactorial disease with moderate heritability and improvements in the phenotypic selection of dogs for breeding should improve subsequent longevity in future generations of Police dogs. Selection of dogs for breeding based on traditional phenotypic scoring, using radiographs of the hips in extension, was shown to be producing minimal improvement in hip status. When compared with distraction radiography, correlation between the two methods was low and they were not equivalent in terms of ranking dogs for susceptibility to hip dysplasia.

In the second part of the thesis, degeneration of the lumbosacral joint was reviewed and the role of surgical management of this condition was examined. A new method of computed tomographic volumetric analysis of the L7-S1 lateral intervertebral neurovascular foramen was described, which can be performed on anaesthetised dogs. This method was then tested on German shepherds, both normal and affected by lumbosacral degeneration. The dogs were imaged in extended, neutral and flexed positions of the lumbosacral junction. Extension results in marked narrowing of the L7-S1 foramina. Dogs affected by degenerative disease of the lumbosacral junction had smaller foraminal volumes than unaffected dogs, indicating that dynamic narrowing likely contributes to clinical signs. An ex-vivo experiment demonstrated that surgical resection of the dorsal annulus and partial L7-S1 discectomy (as commonly performed during dorsal decompressive surgery) may lead to further narrowing of the lateral intervertebral lumbosacral neurovascular canal. A prospective evaluation of a recently developed surgical procedure, dorsolateral foraminotomy, confirmed effective enlargement of the L7-S1 foraminal volume, but showed that by one year there was bone regrowth partially attenuating the effect. Finally, a novel method of dorsal stabilisation, which maintained the foraminal volume by fixation of the lumbosacral junction in a favourable position, was developed through a series of pilot studies, providing the basis for further development.

Table of contents

Abstract		iii
Preface		vii
Abbreviations		xii
Acknowledgements and Funding		xiii
Tables		xv
Figures		xvii
Chapter One	Causes of loss or retirement from active duty of German shepherd dogs in service with the New Zealand Police Dog Section.	1
Chapter Two	Canine Hip Dysplasia in working dogs – Literature Review.	15
Chapter Three	Canine Hip Dysplasia – Determination of improvement in the hip phenotype of the German shepherd dog based on assessment of radiographs in accordance with the New Zealand Veterinary Association Hip Dysplasia Scheme.	45
Chapter Four	An assessment of the agreement between the New Zealand Veterinary Association Hip Dysplasia Scoring System and the PennHIP Distraction Index in German shepherd dogs.	57
Chapter Five	Lumbosacral disease in working dogs – pathogenesis, principles of diagnosis and investigative imaging.	71
Chapter Six	Long-term outcome and ability to return to work of German shepherd dogs after surgical management for degenerative lumbosacral stenosis.	94
Chapter Seven	Dynamic alteration of the lumbosacral intervertebral neurovascular foramen as determined by volumetric analysis using computed tomography.	120
Chapter Eight	Assessment of the effect of dorsal laminectomy and dorsal annulectomy with partial discectomy of the canine L7-S1 intervertebral disc on the volume of the lateral intervertebral neurovascular foramina in dogs when the lumbosacral junction is extended.	136
Chapter Nine	Long-term outcome and CT assessment of lateral foraminotomy in dogs with degenerative lumbosacral stenosis.	143
Chapter Ten	Development of a custom designed implant for dorsal stabilisation of the lumbosacral junction.	159
Summary		180
Appendices		184
Bibliography		211

Abbreviations

ANOVA = Analysis of variance

BVA = British Veterinary Association

CHD = Canine hip dysplasia

CT = Computed tomography

DI = distraction index (PennHIP)

DLS = dorsolateral subluxation score

DLSS = degenerative lumbosacral stenosis

FCI = Federation Cytologique Internationale

GSD = German shepherd dog

KC = Kennel Club (UK)

L = lumbar (nerve or vertebrae)

LS = Lumbosacral

MRI = Magnetic Resonance Imaging

NA = Norberg angle (measured on VD radiographs of the coxofemoral joint)

NZ PDS = New Zealand Police Dog Section

NZVA = New Zealand Veterinary Association

OFA = Orthopedic Foundation for Animals (USA)

PennHIP = The University of Pennsylvania Hip Improvement Program

PL = pelvic limb

VD = ventrodorsal (radiographic beam direction or positioning for surgery)

A study of debilitating orthopaedic conditions of working New Zealand Police German shepherd dogs.

The New Zealand Police force, like many law enforcement agencies around the world, uses the German shepherd dog (GSD) for patrol duties, tracking criminals, apprehension of criminals and armed offender operations. The GSD is known for its intelligence and willingness to work, having been initially bred as a dog for herding cattle.

The GSD is a relatively modern breed of dog. Herding dogs were used throughout Europe in the 18th century with widespread phenotypic variation in their physical and behavioural characteristics. In each local farming community, shepherds selected and bred dogs that they believed possessed desirable characteristics for herding of domestic livestock. The Phylax Society was formed in Germany in 1791 with the intention of creating standardized dog breeds (Strickland *et al.* 1988). However, it was disbanded after only three years due to conflicts amongst members regarding the traits of dogs that the society should promote.

The standardization of a German shepherding dog began in 1899 by Captain Max von Stephanitz (<http://www.suite101.com/content/origin-of-the-german-shepherd-dog>). Having purchased a part-wolf herding dog (which he renamed Horand von Grafrath), he went on to establish a new breed through inbreeding the progeny of that founder sire. Von Stephanitz founded a breed society and named the breed *Deutscher Schäferhund*, literally translating to "German shepherd dog" (Strickland *et al.* 1988).

The direct translation of the name was adopted for use in the official breed registry. However, at the conclusion of World War I (WWI), it was believed that the inclusion of the word "German" would harm the breed's popularity. The breed was officially renamed by the Kennel Club in the United Kingdom as the "Alsatian Wolf Dog" which was also adopted by many other international kennel clubs (Strickland *et al.* 1988). Eventually, the appendage "wolf dog" was dropped. The name Alsatian remained in use for five decades, until 1977, when successful campaigns by dog enthusiasts pressured the British kennel clubs to allow the breed to be registered again as the German Shepherd Dog. The word "Alsatian" still appeared in parentheses as part of the formal breed name and was finally removed in 2010 (Strickland *et al.* 1988).

German shepherd dogs were valuable as military dogs during WWI. They served as messengers, sentries, and guards as well as locating wounded soldiers for the Red Cross. Military working dogs were deployed in World War II, Vietnam and the Middle

East conflicts, and have been valuable in police work, drug detection and search and rescue as well as being excellent guide dogs for the blind and assistants to disabled persons (http://en.wikipedia.org/wiki/German_Shepherd_Dog). German shepherd and Belgian Malinois dogs are specifically chosen for this type of work due to their characteristics (size and high level of drive) and reputation for endurance, speed, strength, courage, intelligence and adaptability to almost any climate (Strickland *et al.* 1988).

The modern German Shepherd dog has been criticized for traits and an appearance different from von Stephanitz's original vision for the breed: that German Shepherd dogs should be bred primarily as working dogs, and that breeding should be strictly controlled to quickly eliminate undesirable traits. Some critics of the breed have commented that careless breeding has promoted inherited disease conditions and anatomical defects.

The history of the New Zealand Police Dog Section (NZPDS) began in 1956 when the then Prime Minister Sir Sidney Holland recruited a police sergeant and his dogs from the English Constabulary of Surrey. A dog training centre was set up in Trentham in conjunction with the Police Training School. Whilst the Police Training School was relocated to Porirua in 1981, the dog training centre has remained at its original site (<http://www.police.govt.nz/service/dogs/history.html>). From those early beginnings the dog section became established and training of dogs for specialist police work began. The first drug-detection training course was held in 1976, which was closely followed by the introduction of explosive detection courses in 1977. More recent developments have seen the introduction of other specialised courses including the Armed Offenders Squad dog course (1992), Accelerated Detection (1997), and Search and Rescue (1998) courses. Currently there are 115 Police Dog Handlers with 90-95 operational dogs and 10-15 in training at any one time (Inspector Brendon Gibson NZPDS pers. comm. 2015)

The operational life of a NZ Police GSD is considered to be approximately eight or nine years (Sergeant Mark Sandford, Breeding Unit Manager, NZPDS pers. comm. 2010) but precise reasons for withdrawal of dogs from service in NZ have not been collated. Each Police dog represents a large financial investment (*circa* \$25,000 NZD) and time commitment for breeding and initial training. An operational team of one dog and one handler requires an annual expenditure of \$120,000 including salary, vehicles, equipment and training (Inspector Brendon Gibson, NZPDS pers. comm. 2012). In order to maximise a Police dog's active working life it is important to identify the major causes of loss and to target strategies to reduce their impact. This is the subject of

chapter one. Degenerative orthopaedic disease has been identified as a major cause of early retirement of working dogs from the United States Military (Moore *et al.* 2001). Specifically, appendicular degenerative joint disease and spinal cord disease were the two conditions most likely to lead to elective euthanasia of military GSDs in that study. Canine hip dysplasia (CHD) and secondary osteoarthritis of the coxo-femoral joints have been reported to be the primary reason for rejection of working dogs during procurement and the most common reason for death/euthanasia in Military working dogs (Olson 1971; Dutton and Moore 1987). As military dogs share many training practices and have similar working conditions to Police dogs, it is likely that any disease incidence will be similar in these two populations. However there is little worldwide data and no specific data from New Zealand on the causes of loss/retirement from work of civilian Police working dogs. Sensibly the NZPDS has employed breeding policies for many years based on international practice, intended to reduce the incidence of CHD.

Hip Dysplasia is a multifactorial developmental disorder with a polygenic mode of inheritance (Cook, Tomlinson *et al.* 1996) [reviewed in chapter two]. Multiple quantitative trait loci associated with CHD have been identified (Lust and Farrell 1977, Mäki *et al.* 2002, Janutta *et al.* 2006). An experimental SNP array, which enables interrogation of genetic variation, is now available but is not yet suitable for the purposes of breeding selection (CanineHD BeadChip, Illumina Inc., San Diego, California, US). Therefore selection of breeding animals in an attempt to reduce the incidence of CHD is currently based on the radiological hip phenotype. There are several schemes based on radiological phenotype in use internationally. Each is based on detection of radiological features of hip dysplasia such as subluxation and degenerative joint disease. The British Veterinary Association Hip Dysplasia Scoring system was introduced in the UK in 1984 and subsequently adopted by the New Zealand Veterinary Association (NZVA). The NZVA has maintained a national computerised database since 1989. Since 1990 the NZPDS has utilised the NZVA hip dysplasia scheme to determine the most suitable dogs to select for breeding. This scheme is based on assessment of a single hip-extended radiograph, using semi-objective scoring criteria (Gibbs 1997). Studies in the UK and the US show a lack of, or only minor, improvement in hip phenotype of successive generations when the standard hip-extended radiograph is used as a selection tool (Corley and Hogan 1985, Willis 1997, Hou *et al.* 2010). Analysis and objective interpretation of the NZVA hip scoring data is required to assess whether the current hip dysplasia screening methods

as used by the NZ Police are effective for selecting dogs with a superior phenotype. This question will be addressed in chapter three.

A new paradigm in the understanding of hip dysplasia has been established with the recognition that coxo-femoral joint laxity is predictive of later osteoarthritis (Smith *et al.* 1990, 1995). A new screening test, utilising distraction radiography (PennHIP), has been developed and the degree of passive laxity has been estimated to have a heritability higher than the radiological score from the hip extended phenotype (Smith *et al.* 1990, 1995, Kapatkin 2002, Janutta and Distl 2006). Despite adoption by the Seeing Eye and other working dog organisations, the PennHIP method had not been adopted as a national scoring scheme anywhere in the world*, and in Europe the Federation Cytologique Internationale (FCI) does not recognise the PennHIP method as a means of CHD assessment. Changes to the reporting of the NZVA scheme from 2003, with a subtotal score in addition to the total score, were proposed to be more useful in determining a dog's hip status (Burbidge 2003). The subtotal score incorporates those radiological criteria present on the hip-extended view associated with coxo-femoral laxity and therefore should be at least partially representative of passive hip laxity. Thus a comparison needed to be performed to determine if the NZVA hip-extended subtotal score identifies the same population of affected dogs as the PennHIP distraction method (chapter four).

In the study by Moore *et al* (2001), "spinal cord disease" ranked second as a cause of death or euthanasia of GSDs in the US Military program. The general term 'spinal cord disease' used in that study includes degenerative intervertebral disc disease, degenerative lumbosacral stenosis (DLSS) and degenerative (GSD) myelopathy. Experience gained at the Massey University Veterinary Teaching Hospital indicates that of these, DLSS is the most prevalent within the NZPDS working dog population. DLSS is characterised by degenerative disc disease and changes to the articulation of the L7-S1 spinal unit with resultant compression of the *cauda equina* (Meij and Bergknut 2010) [reviewed in chapter five]. It has been proposed that working GSDs are predisposed to DLSS due to abnormal anatomical characteristics and/or the particular work they are required to undertake. Subsequent failure of the supportive structures of the lumbosacral (LS) junction is thought to lead to narrowing of the L7-S1 lateral intervertebral neurovascular foramen and LS vertebral canal, with subsequent nerve root and *cauda equina* compression, and clinical signs of pain and neurological dysfunction.

* Until 2014 when it was recommended by the NZVA on the recommendation of the author.

Breeding of GSDs with a lowered propensity to develop DLSS could potentially reduce rates of retirement due to this condition. Whilst transitional vertebral anomalies have been shown to predispose a dog to DLSS (Morgan *et al.* 1993), it is not clear what, if any, more subtle anatomical variations may be contributory to the syndrome. If such predisposing anatomical variations are found and proven to be heritable then breeding selection could be changed to promote better LS conformation. A better understanding of the LS articulation, both anatomically and dynamically, would aid development of new treatment interventions.

Several surgical procedures are promoted as a means of resolving pain and disability in dogs with DLSS but the long-term efficacy of surgery in working dogs with DLSS has been questioned (Linn *et al.* 2003). There is no consensus as to the best strategy for surgical management, whether to perform decompression of the *cauda equina* or stabilisation/fusion of the LS articulation. In order to establish some reference data for future research the long-term clinical success rate of surgical intervention for DLSS in working dogs was investigated using measures of performance in a handler survey, as outlined chapter six.

The effect of angle of the LS junction on the three-dimensional volume of the L7-S1 lateral intervertebral neurovascular foramina will be investigated in chapter seven. Dynamic narrowing of the foramen is considered to be a cause of L7 nerve root compression that contributes to the clinical signs of DLSS. The effect of surgical annulectomy (removal of a section of the dorsal annulus of the L7-S1 intervertebral disc) will be investigated in chapter eight.

A new surgical procedure, lateral foraminotomy, which decompresses the L7-S1 lateral intervertebral neurovascular foramen (Godde and Steffen 2007) offers promise as an effective treatment for DLSS but has not been evaluated long-term. A cohort of dogs were followed to determine if foraminal enlargement is long lasting (chapter nine). Finally, dorsal stabilisation with screws transfixing the adjacent articular processes is widely used to treat DLSS in pet dogs (Slocum and Devine 1986). However, anecdotally, there is a high incidence of implant failure in working dogs. A refinement of trans-fixation of the articular processes, by the addition of pedicle screws, would be considered a novel approach and the success or otherwise of such a procedure should be evaluated. Biomechanical testing could also be used to show the potential strength and failure resistance of the new construct prior to its clinical application. A novel method of dorsal stabilisation is then proposed which uses computer aided design and rapid prototyping technologies to overcome some of the deficiencies of the existing surgical strategies, (chapter ten).

Acknowledgements

I sincerely thank those individuals and organisations that contributed their expertise, or provided data, in support of the investigations for this doctoral thesis.

Sergeant Mark Sandford and Inspector Brendon Gibson of the New Zealand Police Dog Section, Trentham, New Zealand assisted with the survey design and contacting and collating the dog handler's data for chapter one.

Rachel Stratton and Vicki Erceg assisted with the design of the questionnaire and had input into the discussion in chapter one.

Magdeline Soo, a master student under my supervision researched and co-authored the review of Canine Hip Dysplasia. Some sections from chapter two, used material from her Master thesis in Veterinary Medicine. Two co-authored articles from this thesis have been published in the New Zealand Veterinary Journal.

The New Zealand Veterinary Association granted access to their Hip Dysplasia database. From 2008 I have been the Convenor for the NZVA Hip and Elbow Dysplasia panel, an appointee of the Companion Animal Society. On the basis of research described in chapters three and four, and subsequent projects funded by Massey University and the Companion Animal Health Fund (Soo *et al. in press 2014*), the NZVA discontinued traditional hip scoring in favour of recommending PennHIP from 2014.

Richard Laven (Massey University) assisted with the statistical analysis and had input to the discussion for chapter four. Vicki Erceg also contributed to the discussion and was instrumental in the adoption of PennHIP by the New Zealand Police Dog Section. Funding for the study in chapter four was provided by Inspector Brendon Gibson of the Police Dog Service on behalf of the New Zealand Government.

Lauren Blume (BVSc student) generated the lumbosacral angle data from CT images and obtained data for chapter six by contacting police dog handlers.

Angela Hartman (Massey University) contributed to the development of the correct positioning of the dogs for the CT study and to the protocols for the foramen volumetric measurements. In addition she performed many of the 3D reconstructions used as images and assisted with interpretation of the MRI/CT images for chapters six and seven.

Janis Bridges (Massey University) provided assistance with the statistical analysis for all chapters other than chapter four.

The radiographers at the Massey University Veterinary Teaching Hospital, Nicki Moffat, Sonia Torwick, Sharyn Bray and Darryl Newsome are thanked for performing the CT scans. The nursing team of the MUVTH are acknowledged for day-to-day care of clinical cases.

I would like to thank my supervisors Professors Boyd Jones and Joe Mayhew for their many hours of editing and critique and for their guidance through the process.

Finally I would like to thank my wife Susan and my family for their support.

Funding sources

I sincerely thank those organisations that have provided funding in support of the investigations for this doctoral thesis.

The Building Research Capabilities in Strategically Relevant Areas (BRCSRA, NZ Government) Staff Development Fund contributed \$20,000 to the cost of CT imaging which made the lumbosacral studies possible. This money was used to obtain the post-operative data from clinical cases, scanning of normal GSDs and Greyhounds and for the *ex-vivo* experiments in chapters six, seven and eight. Without BRCSRA funding this thesis would not have been possible.

The Massey University Working Dog Centre provided \$11,000 in research grants for the development of the custom made lumbosacral implants described in chapter ten. In addition the Centre provided a travel grant that enabled me to visit the Military Working Dog (MWD) Program, Lackland USAF base in San Antonio Texas. I presented my research and discussed collaborative application of my research to dogs in the US MWD program.

Lauren Blume was supported by a Massey University Summer Scholarship scheme, and a grant from the Massey University Working Dog Centre.

Table	page	
1	<i>Reasons for loss from active service of 134 NZ Police Dogs, lost/retired between 1975 and 2011.</i>	4
2	<i>Mean and median age at date of loss from service as a NZ Police Dog (n=124).</i>	5
3	<i>British Veterinary Association/ Kennel Club (UK) hip dysplasia scoring system.</i>	33
4	<i>Subjective comparisons between the OFA, FCI and BVA/KC scoring systems.</i>	34
5	<i>Reported heritability for the Orthopaedic Foundation for Animals hip grading system, using the hip-extended radiographic view.</i>	40
6	<i>Reported heritability for the Fédération Cynologique Internationale hip grading system, using the hip-extended radiographic view.</i>	41
7	<i>Reported heritability for the British Veterinary Association hip scoring system, using the hip-extended radiographic view.</i>	42
8	<i>Number of bitches whelped each year registered by the New Zealand Kennel Club or scored by the New Zealand Veterinary Association Hip Dysplasia Scheme.</i>	48
9	<i>Mean, SD and median total hip score stratified by year of birth, as recorded by the New Zealand Veterinary Association hip dysplasia scheme for four dog breeds between 1990 and 2008.</i>	48
10	<i>Table showing the number of dogs classified as high or low risk of developing hip dysplasia from a population of German shepherd dogs (N=47) of the NZ PDS.</i>	64
11	<i>Frequency table showing the distribution of the NZVA and PennHIP scores of 47 German shepherd dogs when the scores are classified into high and low risk for development of hip dysplasia.</i>	65
12	<i>Comparison of agreement between the PennHIP distraction index (DI) and the New Zealand Veterinary Association Canine Hip Dysplasia score based on 'high' and 'low' risk thresholds for the development of hip dysplasia.</i>	65
13	<i>Pathology recognised as components of degenerative lumbosacral stenosis in dogs.</i>	84
14	<i>Demographic data and clinical signs of 16 working German shepherd dogs with degenerative lumbosacral stenosis examined at the Massey University Veterinary Teaching Hospital between April 2002 and November 2013.</i>	106
15	<i>Imaging modalities employed, surgical procedure performed and surgical findings in 16 working German shepherd dogs operated at the Massey University Veterinary Teaching Hospital between April 2002 and November 2013 for degenerative lumbosacral stenosis.</i>	107
16	<i>Results of the survey of 16 working German shepherd dogs operated at the Massey University Veterinary Teaching Hospital between April 2002 and November 2013 for degenerative lumbosacral stenosis.</i>	108 109
17	<i>Age, weight and vertebral length comparisons for three groups of dogs used to study the effect of lumbosacral positioning on the three-dimensional volume of the lateral L7-S1 intervertebral neurovascular as measured by computed tomography.</i>	127

Table	page
18 <i>Determination and analysis of the volume of the L7-S1 lateral intervertebral neurovascular foramina in dogs using computed tomography, 3-dimensional reconstruction and an inclusion window region of interest.</i>	128
19 <i>Volumetric analysis of the pooled (left and right) L7-S1 lateral intervertebral neurovascular foramina in dogs using computed tomography.</i>	129
20 <i>The results of the simple linear regression model between position and group using the healthy Greyhound as the comparison group.</i>	129
21 <i>Two by two contingency table to determine the predictive value of foraminal volume using a cut-off value of 90mm³.</i>	132
22 <i>Criteria for classifying the extent of degenerative change of the L7-S1 intervertebral disc evident in 10 large breed dogs by radiological signs.</i>	139
23 <i>L7-S1 lateral intervertebral neurovascular foraminal volume data from cadaveric LS specimens (n=10) measured using CT under a 6.8kg load in cantilever bending (extension), prior to and following annulectomy/partial discectomy of the L7-S1 disc.</i>	140
24 <i>Data from seven dogs diagnosed with degenerative lumbosacral stenosis that underwent lateral foraminotomy.</i>	150
25 <i>Clinical signs, CT findings, treatment performed and outcome of seven dogs with degenerative lumbosacral stenosis that underwent lateral foraminotomy.</i>	151 152
26 <i>Volume of the L7-S1 lateral intervertebral neurovascular foramen in seven dogs, prior to lateral foraminotomy, immediately post-foraminotomy and at follow-up, measured using 3-dimensional CT tissue management protocols.</i>	153
27 <i>Radiological measurements of the L7 pedicle performed on transverse plane CT images of the vertebrae of nine German shepherd Police dogs with degenerative lumbosacral stenosis.</i>	167
28 <i>Mechanical test data on a single bending-to-deformation trial for dorsal stabilisation of acryl-nitrile butadiene styrene plastic lumbosacral junction constructs.</i>	171

Figure	page
1 <i>Cause of loss from active duty as a proportion of all known New Zealand Police German shepherd dogs lost from service between 1975 and 2011 (n=134).</i>	4
2 <i>Box-and-whisker plots for age at loss from service of 124 NZ Police Dogs.</i>	5
3 <i>Kaplan-Meier analysis of 182 New Zealand Police Dogs from date of birth to date of loss from active duty.</i>	6
4 <i>Kaplan-Meier analysis of 182 New Zealand Police Dogs from date of birth to date of loss from active duty. Stratified by cause of loss or retirement.</i>	6
5 <i>Reasons cited for retirement in NZ Police Dog Section German shepherd dogs that were retired from active duty.</i>	7
6 <i>Norberg's angle (NA) and subluxation score (femoral head coverage).</i>	31
7 <i>The PennHIP method of distraction radiography.</i>	36
8 <i>The PennHIP distraction index (DI).</i>	36
9 <i>Distribution graph of the hip dysplasia data collected by the New Zealand Veterinary Association for the German shepherd dog breed.</i>	49
10 <i>A plot of the fitted probabilities for the Norberg Angle score of the pooled hip data of 1087 German Shepherd dogs as recorded in the New Zealand Veterinary Association hip dysplasia database.</i>	50
11 <i>A plot of the fitted probabilities for the subluxation score of the pooled hip data of 1087 German shepherd dogs as recorded in the New Zealand Veterinary Association hip dysplasia database.</i>	50
12 <i>Correlation between the PennHIP score and the New Zealand Veterinary Association subtotal scores for individual hips in 47 German shepherd dogs.</i>	63
13 <i>Relationship between Norberg's angle, subluxation score and PennHIP distraction index in individual hips from 47 German shepherd dogs.</i>	63
14 <i>Normal anatomy of the canine seventh lumbar vertebra.</i>	72
15 <i>Normal anatomy of the canine sacrum.</i>	72
16 <i>Extended ventro-dorsal radiograph of the lumbosacral joint and pelvis of a German Shepherd dog with a transitional vertebra.</i>	73
17 <i>Reconstructed computed tomographic image showing the internal detail of the lumbosacral canal and L7–S1 lateral intervertebral neurovascular foramen of a dog.</i>	75
18 <i>Sagittal 3-dimensional CT reconstruction image of a German Shepherd dog with an osteochondrosis (OCD) lesion (asterisk) affecting the cranio-dorsal aspect of the vertebral body of S1.</i>	77
19 <i>Sagittal CT images of the lumbosacral junction of a German shepherd with typical sacral overhang (left) compared to excessive sacral lamina overhang (middle).</i>	79

Figure		page
20	<i>Lateral CT of a German shepherd dog in extended positioning of the LS junction, demonstrating the lumbosacral angle (Mattoon and Koblik 1993).</i>	80
21	<i>Computed tomographic image of a Labrador retriever showing ventral displacement of the sacrum relative to the L7.</i>	81
22	<i>Axial computed tomographic images of a German shepherd dog demonstrating measurement of the angulation of the articular process joints.</i>	83
23	<i>The lordosis test for the presence of lumbosacral pain in dogs.</i>	86
24	<i>Lateral radiography of the lumbosacral joint in the dog.</i>	87
25	<i>Ventro-dorsal radiography of the lumbosacral joint in the dog.</i>	88
26	<i>Three-dimensional reconstructions of CT data from a German Shepherd dog with signs consistent with degenerative lumbosacral stenosis.</i>	90
27	<i>Sagittal magnetic resonance images of a German shepherd dog with signs of degenerative lumbosacral stenosis.</i>	91
28	<i>Axial magnetic resonance image of a German shepherd dog at the level of the L7–S1 disc space.</i>	92
29	<i>Comparison of extent of dorsal laminectomy.</i>	100
30	<i>Post-operative radiograph of case #8 following bilateral facet joint fixation of the lumbosacral junction.</i>	101
31	<i>Post-operative radiograph of case #7 following bilateral pedicle screw fixation of a transitional lumbosacral junction with two 3.5mm string of pearls plates.</i>	102
32	<i>Pre- and post- operative radiographs of case #14 following SOP + pedicle screws fixation of the lumbosacral joint with two 3.5mm SOP plates.</i>	103
33	<i>Three-dimensional CT reconstructions of a dog, before and after lateral foraminotomy.</i>	103
34	<i>Positioning of the dog on the CT gantry for imaging of the lumbosacral junction.</i>	123
35	<i>Axial CT images of the lumbosacral junction in a GSD, positioned at the pedicle just cranial to the lateral L7-S1 intervertebral neurovascular foramen.</i>	126
36	<i>Scatter plot of the relationship between the length of the L6 (left) and L7 (right) vertebral bodies (cms) and the volume of the lateral L7-S1 intervertebral neurovascular foramen.</i>	128
37	<i>Box plot showing pooled volume data (L and R) of the L7-S1 lateral intervertebral foraminal volume as measured by computed tomography.</i>	130
38	<i>Lumbosacral specimen mounted in a custom jig and placed within the CT gantry, including a diagram of the mounting jig.</i>	138

Figure		page
39	<i>Reconstructed 3-D CT images of the left L7-S1 lateral intervertebral neurovascular foramen of dog #7, pre- and post- lateral foraminotomy.</i>	149
40	<i>Reconstructed CT image of the lumbosacral junction of dog #6.</i>	155
41	<i>Lumbosacral pedicle devices, diagram and cadaver dissection specimen.</i>	162
42	<i>Transverse plane CT images of the lumbosacral junction of a GSD - pedicle length and width measurement.</i>	166
43	<i>Acryl-nitrile butadiene styrene plastic renditions of L7 (left) and the sacrum (right) of a German shepherd dog created from CT data using a Fuse Deposition Modelling 3-Dimensional printer.</i>	169
44	<i>Diagram of the testing jig for lumbosacral junction units printed in plastic and mounted in an Instron materials testing machine.</i>	170
45	<i>Force-displacement curve of a model from group 1, trans-articular screw fixation.</i>	172
46	<i>Force-displacement curve of a model from group 2, bilateral SOP stabilisation.</i>	172
47	<i>Force-displacement curve of a model from group 3, bilateral SOP stabilisation plus trans-articular screw fixation.</i>	173
48	<i>Computer designed titanium implant mounted on Acryl-nitrile butadiene styrene plastic renditions of L7 and the sacrum of a German shepherd dog.</i>	175
49	<i>Force-displacement curve of a stabilised LS junction model with a custom made titanium implant.</i>	176
50	<i>Computer generated 3-dimensional model of the LS junction of a dog with degenerative lumbosacral stenosis.</i>	177
51	<i>Intra-operative images of the application of a novel computer-designed titanium implant to the LS junction of an eighteen month old Akita with degenerative lumbosacral stenosis.</i>	178
52	<i>Post-operative radiographs following application of a novel computer-designed titanium implant to the LS junction of an eighteen month old Akita with DLSS.</i>	178
53	<i>Six week post-operative radiographs following application of a novel computer-designed titanium implant to the LS junction of an eighteen month old Akita with DLSS</i>	179