EVALUATION OF A THREE-DIMENSIONAL KINEMATIC MODEL OF THE HINDLIMB IN DOGS

by

BRYAN THOMAS TORRES

(Under the Direction of Steven Budsberg)

ABSTRACT

Clinical kinematic studies have been underutilized in veterinary medicine. Previous studies have focused on hindlimb joint motion with respect to flexion and extension utilizing a linear-link model to define sagittal plane motion; however, joint movement is complex and incompletely represented in a two-dimensional (2-D) model. While 2-D models provide accurate and repeatable information about uniplanar motion they are limited in their ability to assess true three-dimensional (3-D) joint motion. The Joint Coordinate System (JCS) was developed to describe 3-D joint motion by 6 independent coordinates or 6 degrees of freedom. Additionally, it facilitates the description and understanding of joint motion between biomechanical and clinical fields. The benefit of a segmental rigid-body model, such as the JCS, is that it provides an anatomically accurate and clinically relevant 3-D description of joint motion with six degrees of freedom.

These studies were performed to provide the initial description of a 3-D segmental rigid-body model of the hindlimb of the dog based on the JCS. Additionally, to compare this new 3-D model to previous 2-D models, and describe the effect of known sources of kinematic variability on this model. The results of the first study established that the new 3-D model produces similar

sagittal plane kinematics to previously established 2-D models; while providing additional information regarding the transverse and frontal planes of joint motion. The second study found that changes in marker placement alter kinematic data similarly for the 3-D and 2-D models. For both models, the greatest degree of change was found when placement errors occurred in the craniocaudal direction. The third study established that inter- and intra-examiner variability occurs with the 3-D model. Similar findings have been shown with 2D models. However, experience with the 3D model reduced overall variability and resulted in consistent and repeatable sagittal plane kinematic data collection. The final study evaluated the effect of different modes of ambulation (overground versus treadmill) on the 3-D kinematic model. We found that while both modes produce similar gait waveforms, only sagittal plane data was unaffected by mode of ambulation.

INDEX WORDS: Kinematics, Gait Analysis, Joint Motion, Stifle, Canine, Dog

EVALUATION OF A THREE-DIMENSIONAL KINEMATIC MODEL OF THE HINDLIMB IN DOGS

by

BRYAN THOMAS TORRES

DVM, University of Georgia, 2003

Diplomate, American College of Veterinary Surgeons, 2014

A Dissertation Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2015

EVALUATION OF A THREE-DIMENSIONAL KINEMATIC MODEL OF THE HINDLIMB IN DOGS

by

BRYAN THOMAS TORRES

Major Professor: Steven Budsberg

Committee: Scott Brown
Timothy Foutz

Electronic Version Approved:

Suzanne Barbour
Dean of the Graduate School
The University of Georgia
August 2015

DEDICATION

I would like to thank my parents, my mother- and father-in-law Peggy and James Harrington, my wife Jennifer Harrington, and my children, James and Fionn Torres, for their love and support. Mom and Dad, thank you for your constant encouragement and many sacrifices through the years. I strive everyday to live up to the example that you set as people and as parents. Jim and Peggy, thank you for all that you have done and for your constant support throughout this process. Jennifer, you made this journey possible, bearable, and without you I would be lost. To James and Fionn, you are truly my greatest accomplishments. You all have made this journey worthwhile.

ACKNOWLEDGEMENTS

I would like to thank Steven Budsberg for his constant support and guidance during my veterinary and graduate education. Throughout my time at the University of Georgia he has served in many roles—teacher, senior clinician, resident advisor, major professor, colleague, mentor, but most importantly, friend. I will strive to live up to the example that you have set. I hope to be able to do for others what you have done for me.

To my committee members, Tim Foutz and Scott Brown. Thank you for your support and encouragement. I have truly valued your guidance throughout my veterinary and graduate school education.

To Lisa Reynolds and Megan Hansen. Thank you for your help and friendship through the years, for filling the office with laughter, and for making every day enjoyable.

To my generous collaborators Yang-Chieh Fu, John Punke, Judy Navik, Andrew Sornborger, Dana Whitlock, Peter Gilbert, Noel Moens, Abbie Speas, and Sami Al-Nadaf. I will be forever grateful for your help and without you this work would not have been possible.

To the faculty, students, residents, and interns, and staff of the University of Georgia, College of Veterinary Medicine. The opportunity to work with such an incredible group of people has been one of the greatest honors of my life.

TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS v

LIST OF TABLES viii

LIST OF FIGURES x

CHAPTER

1 INTRODUCTION AND LITERATURE REVIEW 1

Marker Placement and Skin Motion Artifact 2

Repeatability 4

Mode of Ambulation 5

References 7

2 COMPARISON OF CANINE STIFLE KINEMATIC DATA COLLECTED WITH THREE DIFFERENT TARGETING MODELS 13

Abstract 14

Introduction 15

Materials and Methods 16

Results 21

Discussion 22

References 27

3 THE EFFECT OF MARKER LOCATION VARIABILITY ON NONINVASIVE CANINE STIFLE KINEMATICS 40

Abstract 41

Introduction 42

Materials and Methods 42

Results 45

Discussion 46

References 49

4 THE EFFECT OF EXAMINER VARIABILIY ON MULTIPLE CANINE STIFLE KINEMATIC GAIT COLLECTIONS IN A 3-DIMENSIONAL MODEL 56

Abstract 57

Introduction 58

Materials and Methods 58

Results 61

Discussion 62

References 67

5 COMPARISON OF OVERGROUND AND TREADMILL-BASED GAIT OF DOGS 75

Abstract 76

Introduction 77

Materials and Methods 77

Results 81

Discussion 82

References 86

6 CONCLUSION 95

LIST OF TABLES

Page

Table 2.1: Marker locations for Joint Coordinate System Kinematic Modeling of a Canine Stifle Unilaterally 31

Table 2.2: Mean Fourier Coefficients from All Methods for the Sagittal Femorotibial Joint Angle in all Dogs at a Walk and Trot 32

Table 3.1: Marker Locations for Kinematic Modeling of a Canine Stifle Unilaterally.....51

Table 4.1: Anatomic Landmarks for Skin Marker Locations for Kinematic Modeling of a Canine Hindlimb 71

Table 4.2: Results (Tukey-Adjusted P-Value) of Intra-Examiner Fourier Analysis for Examiner A (Experienced) 72

Table 4.3: Results (Tukey-Adjusted P-Value) of Intra-Examiner Fourier Analysis for Examiner B (Novice) 73

Table 4.4: Results (P-Value) of Inter-Examiner Fourier Analysis Between Examiners A (Experienced) and B (Novice) 74

Table 5.1: Bilateral marker locations for joint coordinate system kinematic modeling of the hip, femorotibial, and tarsal joints of dogs.....89

Table 5.2: Mean Fourier coefficients derived for the right hip, femorotibial, and tarsal joints of 5 dogs in an assessment of sagittal (flexion-extension) plane kinematics of overground and treadmill-based gaits during walking and trotting 90

Table 5.3: Mean Fourier coefficients derived for the right hip, femorotibial, and tarsal joints of 5 dogs in an assessment of transverse (internal-external rotation) plane kinematics of overground and treadmill-based gaits during walking and trotting 91

Table 5.4: Mean Fourier coefficients derived for the right hip, femorotibial, and tarsal joints of 5 dogs in an assessment of frontal (abduction-adduction) plane kinematics of overground and treadmill-based gaits during walking and trotting 92

LIST OF FIGURES

Page

Figure 2.1: Illustrative representation of the body segments and kinematic marker placement on the skin of the canine hind limb 33

Figure 2.2: Graphs of mean stifle flexion and extension angles for all dogs at a walk and a trot with all 3 methods illustrated 34

Figure 2.3: Mean stifle flexion and extension angle at a walk (A) and trot (B) with 95% confidence intervals for an individual dog measured with differing methods 36

Figure 2.4: Mean stifle flexion and extension angle at a walk and trot with 95% confidence intervals of two different dogs 38

Figure 3.1: Illustrative representation of the body segments and kinematic marker placement on the skin of the canine hind limb 52

Figure 3.2: Graphs of mean stifle flexion and extension angles for all dogs at a walk and a trot with all 3 methods and greater trochanter (GT) locations illustrated 53

Figure 3.3: Mean stifle flexion and extension angle with Joint Coordinate System Model (JCS) at a trot with 95% confidence intervals for an individual dog measured with differing greater trochanter (GT) locations 54

Figure 4.1: Mean (solid lines) stifle angles with 95% confidence intervals (dashed lines) obtained during testing days 1–4 from 6 dogs in a study of sagittal (flexion-extension [Flex-Ext]), transverse (internal-external rotation [Int-Ext]), and frontal (abduction–adduction [Abd–Add]) plane kinematics during a trot 70

Figure 5.1: Graphs illustrating the mean (solid lines) joint angles with 95% confidence intervals (dashed lines) obtained for the hip (left column), femorotibial (central column), and tarsal (right column) joints of 5 dogs in a study of sagittal (flexion-extension [Flex-ext]), transverse (internal-external rotation [Int-ext]), and frontal (abduction-adduction [Abd-add]) plane kinematics during overground (black lines) or treadmill-based (red lines) ambulation.....93

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Kinematic studies on the canine hindlimb using superficial skin marker systems have become popular in recent decades. These studies utilize specialized cameras to track strategically placed markers on predetermined locations (primarily anatomical landmarks) on the dog for collection of kinematic data. Markers may consist of attached light emitting diodes (LED's)[1-3] or retro-reflective markers.[4-15] However, compared to the extensive three-dimensional (3-D) kinematic studies in human subjects,[16-18] most studies in veterinary medicine on dogs have been limited to two-dimensions (2-D).[19-23] In part, this is because of the reduced expense of 2-D kinematic systems. These 2-D systems can obtain accurate and repeatable sagittal plane data; however, 2-D systems suffer from parallax error and simultaneous collection of transverse and frontal planes of motion is not possible.[24] The benefit of 3-D systems is their ability to simultaneously collect all planes of joint motion providing complete 3-D motion data. Previously, 3-D kinematic systems have been used to report uniplanar (sagittal) joint motion in dogs.[10,12-14] However, these studies utilized simple linear-link models with laterally applied markers—thus, limiting their ability to assess true three-dimensional joint motion. Until recently, the only 3-D kinematic data in veterinary medicine has been collected with the aid of invasive external fixators,[26] stereo radiographic methods,[27,28] or in cadaveric models.[29] Recently, a 3-D segmental rigid-body model of the complete hindlimb of a dog has been described.[4] This model utilizes a superficial skin marking system to describe 3-D joint motion by use of 6 independent

coordinates or 6 degrees of freedom.[25] The benefit of this type of model is that it provides an anatomically accurate and clinically relevant 3-D description of joint motion with 6 degrees of freedom. It integrates techniques and algorithms developed for human biomechanical studies[4,30-32] resulting in an advanced biomechanical analysis not previously utilized in veterinary medicine. To the author's knowledge there are no studies that compare this new 3-D kinematic model to previously described 2-D models or evaluate the effect of known sources of variability with superficial skin marking systems. Thus, the work describe here will attempt to address these areas.

Marker Placement And Skin Motion Artifact

Skin movement artifact and the effect on skin marker system for non-invasive kinematic evaluation of joint motion has been a longstanding concern in both human and veterinary gait analysis. Ideally, for accurate evaluation of joint motion the markers delineating the targeted bones should be rigidly affixed to the skeletal system so as to provide precise representations of bone motion. However, rigid fixation requires invasive measures and long surgical recovery times prior to data collection that are not conducive to applications in the clinical setting.[33,34] Therefore, the use of retroreflective markers placed on the skin has proven more clinically feasible. A recent study evaluated soft tissue movement artifact in an ovine study model using both skeletally mounted markers and skin markers, simultaneously.[34] They noted that skin marker motion was greatest in areas with more underlying soft tissue and they found an average peak error of 16, 5, and 3mm for the hip, knee, and tarsus, respectively. Similar findings have been found in dogs when utilizing a sagittal superficial skin marker systems.[15] In that study the greatest degree of skin movement occurred around the stifle and hip—areas with greater skin soft

tissue coverage as compared to the tarsus. Additionally, a cyclic pattern of skin motion was demonstrated to occur throughout the gait cycle. Research in horses has indicated that correction for skin marker movement is mandatory and that without correction, up to 15 degrees of error may exist in evaluation of the knee angle.[35] Unfortunately, direct comparison between rigidly affixed and skin markers in dogs has not been evaluated at this time.

A common strategy employed when developing kinematic models is to place skin markers over bony landmarks, where possible. This has two main advantages: 1) it provides for an easily palpable and repeatable location for marker attachment; 2) it selects for marker locations with minimal underlying soft tissue, which may help decrease skin and soft tissue movement artifact. Kim et al.,[15] recently evaluated skin movement artifact in a superficial skin marker model of the canine hind limb. They found that skin movement affected gait data and that these changes occurred in a cyclic pattern throughout the gait cycle. Recommendations were made to characterize skin movement in canine kinematics to improve skin marker systems and more accurately represent underlying bone movement.[15] However, skin movement must be evaluated at all sites of marker attachment present in the model utilized for data collection. Until additional data is available regarding skin marker movement at all marker attachment sites, it must be presupposed that kinematic data has some degree of skin movement artifact present that is unrelated to movement of the underlying bones.[13]

In the newly proposed 3-D model,[4] a static trial of each dog is collected and the marker relationships are analyzed to minimize the effect of skin movement and marker drop-out during dynamic motion.[30,36] The use of this technique established the use of "virtual markers," which are beneficial when increased skin motion artifact is present and when overall marker visibility is of concern. One unique complication superficial skin marking systems in veterinary medicine is

the visibility of medially located markers during ambulation. While the dog is moving, the trunk may partially or completely conceal from camera view any markers located on the medial aspect of the legs. This problem has not been described in the previous 2-D models as those models only utilize markers placed on the lateral aspect of the body, an area that is highly visible. This new 3-D model addressed this issue with the removal of medial markers during dynamic gait and subsequent mathematical reconstruction from an initial static trial. The use of this technique utilizing an unweighted least squared method[30] allows for the minimization of the overall effect of skin motion artifact and reduces the need for constant visibility of all markers.[4]

Repeatability

Three-dimensional kinematic analysis is becoming more common and has been proven useful in the study of normal and pathologic locomotion.[11,13] However, for this analytical tool to become widely accepted as useful and clinically relevant in veterinary medicine, its repeatability and sources of variability must be established.

Experience level with a kinematic model and familiarity with anatomic landmarks may affect data collection and overall data variability. It has been shown that errors in marker placement can change the gait waveform.[13] Minor inconsistencies in marker location cause a shift in the vertical position of the gait waveform. This finding resulted in a recommendation for kinematic waveform data normalization.[12,13] However, a recent study demonstrated that waveform normalization reduces but does not eliminate differences between individual dogs and the evaluation of pooled data is unaffected.[8] Others have found that differences between testing times are more likely due to changes in the gait patterns of subjects and less related to marker location inconsistencies.[37,38] It is likely that kinematic data variability is due to the additive effect

of multiple small differences present on each testing day—attributed to the testing environment, equipment, patient, primary examiner, etc.

Previous research has established sources of variability for kinetic data.[39] However, there are no reports establishing the repeatability and sources of variability during 3-D kinematic testing. Additionally, no data is available regarding repeatability and sources of variability while using the new 3-D model recently developed.[4]

Mode Of Ambulation

Kinematic data in dogs has been collected for years on patients during both overground and treadmill based ambulation. The use of treadmills provides the ability to collect a large quantity of data rapidly with the utilization of minimal laboratory space. However, debate continues regarding the use of treadmills for the collection of gait data. In human medicine treadmill based gait assessment is widely employed. For research purposes, a distinct advantage is the ability to control such variables as lighting, surface, and velocity.[40-42] However, it has been shown that variability exists between overground and treadmill based gait in humans during a walk[43] and run.[44] In veterinary medicine, both kinetic and kinematic gait evaluations have been performed using data collected by either over ground[45-49] or treadmill based[11,41,50-52] ambulation. While differences have been described in overground and treadmill based gait it has been argued that if the treadmill belt speed is constant, and similar to overground velocity, then biomechanically there should be no differences between the two modes of locomotion.[53] However, experimental studies have concluded that differences exist.[43,44,54,55] Savelberg et al in 1998[55] concluded that intra-stride belt-speed variation can lead to kinematic differences between overground and treadmill gait. Additionally, these differences are related to the overall power of

the treadmill and the mass of the subject. Furthermore, treadmill based gait has been shown to alter joint range-of-motion.[54,56] Lee et al.,[54] in 2008 evaluated human gait during overground and treadmill based walking. On evaluation of sagittal plane kinematics they found a decreased knee range-of-motion during treadmill walking. This is supported by other studies that have found decreased joint range-of-motion during treadmill based gait.[56] Interestingly, they found very few overall differences in walking overground or on treadmills and concluded that this was due to muscular adaptations (modifications in muscle activation and joint moments and powers) occurring during treadmill based gait that produce similar joint kinematics for overground and treadmill ambulation.[54]

Treadmill use requires habituation for use in gait analysis. Humans and animals require sufficient time and training to become accustomed to treadmill based gait.[42,43,57] Matsas in 1984[57] found that in humans, treadmill based walking could be generalized to overground walking after 6 minutes of treadmill use—indicating that a period of familiarization may be needed to produce comparable gaits. In veterinary medicine, reliable fore- and rear limb kinematic measurements have been demonstrated within 30 seconds of treadmill use.[52] However, a separate study found that gait consistency was not achieved after 2 minutes of treadmill use.[41] Recently, a study demonstrated habituation to treadmill use over a two-week training period.[58] As with kinetic data acquisition on treadmills, demonstrated differences exist between it and overground movement.[59] Clearly, debate still exists as to the use of treadmills in the reliable and repeatable acquisition of kinematic data. Unfortunately, to the authors' knowledge there are currently no studies that compare canine kinematic data, whether with a 2-D or 3-D model, obtained during overground and treadmill based ambulation.

References

1. Zhu Q, Larson CR, Sjovold SG, et al: Biomechanical evaluation of the Total Facet Arthroplasty System: 3-dimensional kinematics. Spine (Phila Pa 1976) 32:55-62, 2007.

2. Goel VK, Kong W, Han JS, et al: A combined finite element and optimization investigation of lumbar spine mechanics with and without muscles. Spine (Phila Pa 1976) 18:1531-1541, 1993.

3. Milner TE, Ijaz MM: The effect of accuracy constraints on three-dimensional movement kinematics. Neuroscience 35:365-374, 1990.

4. Fu YC, Torres BT, Budsberg SC: Evaluation of a three-dimensional kinematic model for canine gait analysis. Am J Vet Res 71:1118-1122, 2010.

5. Torres BT, Gilbert PJ, Reynolds LR, et al: The Effect of Examiner Variability on Multiple Canine Stifle Kinematic Gait Collections in a 3-Dimensional Model. Vet Surg, 2014.

6. Torres BT, Moens NM, Al-Nadaf S, et al: Comparison of overground and treadmill-based gaits of dogs. Am J Vet Res 74:535-541, 2013.

7. Torres BT, Punke JP, Fu YC, et al: Comparison of canine stifle kinematic data collected with three different targeting models. Vet Surg 39:504-512, 2010.

8. Torres BT, Whitlock D, Reynolds LR, et al: The effect of marker location variability on noninvasive canine stifle kinematics. Vet Surg 40:715-719, 2011.

9. Allen K, DeCamp C, Braden T, et al: Kinematic gait analysis of the trot in healthy mixed breed dogs. Vet Compend Orthop Trauma 7:148-153, 1994.

10. Bennett RL, DeCamp CE, Flo GL, et al: Kinematic gait analysis in dogs with hip dysplasia. Am J Vet Res 57:966-971, 1996.

11. Bockstahler BA, Henninger W, Muller M, et al: Influence of borderline hip dysplasia on joint kinematics of clinically sound Belgian Shepherd dogs. Am J Vet Res 68:271-276, 2007.

12. DeCamp CE, Riggs CM, Olivier NB, et al: Kinematic evaluation of gait in dogs with cranial cruciate ligament rupture. Am J Vet Res 57:120-126, 1996.

13. DeCamp CE, Soutas-Little RW, Hauptman J, et al: Kinematic gait analysis of the trot in healthy greyhounds. Am J Vet Res 54:627-634, 1993.

14. Hottinger HA, DeCamp CE, Olivier NB, et al: Noninvasive kinematic analysis of the walk in healthy large-breed dogs. Am J Vet Res 57:381-388, 1996.

15. Kim SY, Kim JY, Hayashi K, et al: Skin movement during the kinematic analysis of the canine pelvic limb. Vet Comp Orthop Traumatol 24:326-332, 2011.

16. Andriacchi TP, Alexander EJ: Studies of human locomotion: past, present and future. Journal of Biomechanics 33:1217-1224, 2000.

17. Gage JR: The clinical use of kinematics for evaluation of pathological gait cerebral palsy. Journal of Bone and Joint Surgery 76-A:622-631, 1994.

18. Gage JR, Deluca PA, Renshaw T, S.: Gait analysis: Principles and applications. Journal of Bone and Joint Surgery 77-A:1607-1623, 1995.

19. DeCamp CE, Soutas-Little RW, Hauptman J, et al: Kinematic gait analysis of the trot in healthy greyhounds. American journal of veterinary research 54:627-634, 1993.

20. Vilensky JA, O'Connor BL, Brandt KD, et al: Serial kinematic analysis of the canine hindlimb joints after deafferentation and anterior cruciate ligament transection. Osteoarthritis and Cartilage 5:173-182, 1997.

21. Poy NSJ, DeCamp CE, Bennett RL, et al: Additional kinematic variables to describe differences in the trot between clinically normal dogs and dogs with hip dysplasia. American Journal Of Veterinary Research 61:974-978, 2000.

22. Marsolais GS, McLean S, Derrick T, et al: Kinematic analysis of the hind limb during swimming and walking in healthy dogs and dogs with surgically corrected cranial cruciate ligament rupture. Journal of the American Veterinary Medical Association 222:739-743, 2003.

23. Bockstahler BA, Henninger W, Muller M, et al: Influence of borderline hip dysplasia on joint kinematics of clinically sound Belgian Shepherd dogs. American Journal of Veterinary Research 68:271-276, 2007.

24. Kim J, Rietdyk S, Breur GJ: Comparison of two-dimensional and three-dimensional systems for kinematic analysis of the sagittal motion of canine hind limbs during walking. Am J Vet Res 69:1116-1122, 2008.

25. Grood ES, Suntay WJ: A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J Biomech Eng 105:136-144, 1983.

26. Korvick DL, Pijanowski GJ, Schaeffer DJ: Three-dimensional kinematics of the intact and cranial cruciate ligament-deficient stifle of dogs. Journal of Biomechanics 27:77-87, 1994.

27. Tashman S, Aderst W, Kolowich P, et al: Kinematics of the ACL-deficient canine knee during gait: serial changes over two years. Journal of Orthopaedic Research 22:931-941, 2004.

28. Anderst WJ, Les C, Tashman S: In vivo serial joint space measurements during dynamic loading in a canine model of osteoarthritis. Osteoarthritis and Cartilage 13:808-816, 2005.

29. Chailleux N, Lussier B, De Guise J, et al: In vitro 3-dimensional kinematic evaluation of 2 corrective operations for cranial cruciate ligament-deficient stifle. Canadian Journal of Veterinary Research 71:175-180, 2007.

30. Veldpaus FE, Woltring HJ, Dortmans LJ: A least-squares algorithm for the equiform transformation from spatial marker co-ordinates. J Biomech 21:45-54, 1988.

31. Wu G, Cavanagh PR: ISB recommendations for standardization in the reporting of kinematic data. J Biomech 28:1257-1261, 1995.

32. Woltring HJ: A FORTRAN package for generalized, cross-validatory spline smoothing and differentiation. Advances in Engineering Software (1978) 8:104-113, 1986.

33. Korvick DL, Pijanowski GJ, Schaeffer DJ: Three-dimensional kinematics of the intact and cranial cruciate ligament-deficient stifle of dogs. J Biomech 27:77-87, 1994.

34. Taylor WR, Ehrig RM, Duda GN, et al: On the influence of soft tissue coverage in the determination of bone kinematics using skin markers. J Orthop Res 23:726-734, 2005.

35. van den Bogert AJ, van Weeren PR, Schamhardt HC: Correction for skin displacement errors in movement analysis of the horse. J Biomech 23:97-101, 1990.

36. Cappello A, La Palombara PF, Leardini A: Optimization and smoothing techniques in movement analysis. Int J Biomed Comput 41:137-151, 1996.

37. Gorton GE, 3rd, Hebert DA, Gannotti ME: Assessment of the kinematic variability among 12 motion analysis laboratories. Gait Posture 29:398-402, 2009.

38. Kadaba MP, Ramakrishnan HK, Wootten ME, et al: Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. J Orthop Res 7:849-860, 1989.

39. Rumph PF, Steiss JE, West MS: Interday variation in vertical ground reaction force in clinically normal Greyhounds at the trot. Am J Vet Res 60:679-683, 1999.

40. Keegan KG, Wilson DA, Wilson DJ, et al: Evaluation of mild lameness in horses trotting on a treadmill by clinicians and interns or residents and correlation of their assessments with kinematic gait analysis. Am J Vet Res 59:1370-1377, 1998.

41. Clements DN, Owen MR, Carmichael S, et al: Kinematic analysis of the gait of 10 labrador retrievers during treadmill locomotion. Vet Rec 156:478-481, 2005.

42. Vilensky JA, O'Connor BL, Brandt KD, et al: Serial kinematic analysis of the canine hindlimb joints after deafferentation and anterior cruciate ligament transection. Osteoarthritis Cartilage 5:173-182, 1997.

43. Alton F, Baldey L, Caplan S, et al: A kinematic comparison of overground and treadmill walking. Clin Biomech (Bristol, Avon) 13:434-440, 1998.

44. Wank V, Frick U, Schmidtbleicher D: Kinematics and electromyography of lower limb muscles in overground and treadmill running. Int J Sports Med 19:455-461, 1998.

45. Budsberg SC, Chambers JN, Lue SL, et al: Prospective evaluation of ground reaction forces in dogs undergoing unilateral total hip replacement. Am J Vet Res 57:1781-1785, 1996.

46. Budsberg SC, Jevens DJ, Brown J, et al: Evaluation of limb symmetry indices, using ground reaction forces in healthy dogs. Am J Vet Res 54:1569-1574, 1993.

47. Budsberg SC, Verstraete MC, Brown J, et al: Vertical loading rates in clinically normal dogs at a trot. Am J Vet Res 56:1275-1280, 1995.

48. Budsberg SC, Verstraete MC, Soutas-Little RW: Force plate analysis of the walking gait in healthy dogs. Am J Vet Res 48:915-918, 1987.

49. Budsberg SC, Verstraete MC, Soutas-Little RW, et al: Force plate analyses before and after stabilization of canine stifles for cruciate injury. Am J Vet Res 49:1522-1524, 1988.

50. Brebner NS, Moens NM, Runciman JR: Evaluation of a treadmill with integrated force plates for kinetic gait analysis of sound and lame dogs at a trot. Vet Comp Orthop Traumatol 19:205-212, 2006.

51. Bockstahler BA, Skalicky M, Peham C, et al: Reliability of ground reaction forces measured on a treadmill system in healthy dogs. Vet J 173:373-378, 2007.

52. Owen M, Richards J, Clements D, et al: Kinematics of the elbow and stifle joints in greyhounds during treadmill trotting – An investigation of familiarisation. Vet Comp Orthop Traumatol 17:141-140, 2004.

53. van Ingen Schenau GJ: Some fundamental aspects of the biomechanics of overground versus treadmill locomotion. Med Sci Sports Exerc 12:257-261, 1980.

54. Lee SJ, Hidler J: Biomechanics of overground vs. treadmill walking in healthy individuals. J Appl Physiol 104:747-755, 2008.

55. Savelberg HH, Vorstenbosch MA, Kamman EH, et al: Intra-stride belt-speed variation affects treadmill locomotion. Gait Posture 7:26-34, 1998.

56. Watt JR, Franz JR, Jackson K, et al: A three-dimensional kinematic and kinetic comparison of overground and treadmill walking in healthy elderly subjects. Clin Biomech (Bristol, Avon) 25:444-449, 2010.

57. Matsas A, Taylor N, McBurney H: Knee joint kinematics from familiarised treadmill walking can be generalised to overground walking in young unimpaired subjects. Gait Posture 11:46-53, 2000.

58. Al-Nadaf S, Torres BT, Budsberg SC: Comparison of two methods for analyzing kinetic gait data in dogs. Am J Vet Res 73:189-193, 2012.

59. Buchner HH, Savelberg HH, Schamhardt HC, et al: Kinematics of treadmill versus overground locomotion in horses. Vet Q 16 Suppl 2:S87-90, 1994.

CHAPTER 2

COMPARISON OF CANINE STIFLE KINEMATIC DATA COLLECTED WITH THREE DIFFERENT TARGETING MODELS[1]

[1]Torres, B.T., Punke J.P., Fu Y.C., Navik J.A., Speas A.L., Sornborger A., Budsberg S.C. 2010. *Veterinary surgery*. 39.4: 504-512. Reprinted here with permission of publisher.

Abstract

Objective: To model the kinematics of the canine stifle in 3 dimensions using the Joint Coordinate System (JCS) and compare the JCS method with linear and segmental models.

Study Design: In vivo biomechanical study.

Animals: Normal adult mixed breed dogs (n = 6).

Methods: Dogs had 10 retroreflective markers affixed to the skin on the right pelvic limb. Dogs were walked and trotted 5 times through the calibrated space and the procedure was repeated 5 days later. Sagittal flexion and extension angle waveforms acquired during each trial with all 3 models (JCS, Linear, and Segmental) were produced simultaneously during each gait. The JCS method provided additional internal/external and abduction/adduction angles. Comparison of sagittal flexion and extension angle waveforms was performed with generalized indicator function analysis (GIFA) and Fourier analysis. A normalization procedure was performed.

Results: Each model provided consistent equivalent sagittal flexion–extension data. The JCS provided consistent additional internal/external and abduction/adduction. Sagittal waveform differences were found between methods and testing days for each dog at a walk and a trot with both GIFA and Fourier analysis. After normalization, differences were less with Fourier analysis and were unaltered with GIFA.

Conclusions: Whereas all methods produced similar flexion–extension waveforms, JCS provided additional valuable data.

Clinical Relevance: The JCS model provided sagittal plane flexion/extension data as well as internal/external rotation and abduction/adduction data.

Introduction

Clinical kinematic studies have been under used in veterinary medicine.[1] Previously, studies have focused on joint motion with respect to flexion and extension; however, joint movement is complex and incompletely represented in a 2-dimensional (2-D) model.[2] Interestingly, recent evidence has indicated that kinematic evaluation may be more sensitive than force platform, or kinetic, evaluation for detection of subclinical orthopedic disease.[3]

Historically, linear-link models of the canine hindlimb have been used to define sagittal plane motion.[4–7] Whereas these models provide accurate and repeatable information about uniplanar motion they are limited in their ability to assess true 3-D joint motion. The Joint Coordinate System (JCS) was developed to describe 3-D joint motion by 6 independent coordinates or 6 degrees of freedom. Additionally, it facilitates the description and understanding of joint motion between biomechanical and clinical fields.[2] The benefit of a segmental rigid-body model, such as the JCS, is that it provides an anatomically accurate and clinically relevant 3-D description of joint motion with 6 degrees of freedom.

Whereas analysis of kinematic gait data in veterinary medicine has often focused on associated gait waveforms, analysis methodology has varied. Gait waveforms have been analyzed with polynomial equations[6,8]; Fourier analysis[4,5,7,9]; and principal component analysis.[10] Another methodology that may prove useful in the evaluation of canine gait waveforms is generalized indicator function analysis (GIFA).[11] This is a multivariate vector waveform analysis method that maximizes signal power while maintaining a large signal-to-noise ratio, and provides the ability to assess differences at specific points along the waveforms.

Our purpose was to model 3-D kinematics of the canine stifle with the JCS,[12] and compare the JCS method with more traditional sagittal plane models of the canine stifle. Our

hypothesis was that the JCS model would provide sagittal plane flexion/extension femorotibial angles comparable with those of more traditional sagittal plane models while also supplying internal/external rotation and abduction/adduction data. We also hypothesized that use of GIFA for waveform analysis will prove comparable to Fourier analysis, a more familiar frequency spectrum reconstruction analysis methodology.[4,5,7]

Materials And Methods

Dogs

Adult dogs (n = 6; weighing, 20–30 kg) with normal bilateral hip and stifle radiographs and no detectable pathologic changes, from an established research colony were studied. Force plate gait analysis, hematologic and serum biochemical profiles, and complete physical examinations were performed before study start and no abnormalities were detected. Dogs were housed indoors in a climate-controlled environment and fed commercially available dog food ad libitum.

Motion Collection

Ten spherical retroreflective markers (8 mm diameter) were fixed with double-sided tape and cyanoacrylate to the right pelvic limb (Table 2.1). A 3-D testing space was established on a 13 m walkway. Right-handed orthogonal coordinate axes were used to describe the testing space in 3-D with 0, 0, 0 (X, Y, Z) located in the center of the testing space. Cameras captured sample data at 200 Hz. Before each day's collection, the system was calibrated with a calibration frame (Vicon Peak Motus L-Frame, Vicon-Peak, Vicon Motion Systems Inc., Centennial, CO) of known dimensions and by dynamic linearization with a custom made 0.700 m wand. Marker

locations were captured by a kinematic system of 6 infrared cameras (Vicon MX03, Vicon Motion Systems Inc.) arranged around the gait platform. Data were recorded and analyzed by a motion-analysis program (Peak Motus 8.5, Vicon Motion Systems Inc.).

Initially, a static trial of each dog was collected. Four markers (see *, Table 2.1) were removed during subsequent dynamic trials. These markers were mathematically reconstructed from the initial static trial and were used as virtual markers during the dynamic trials.[13–16] This was necessitated by limitations in marker visibility while gaiting because of the partial or complete truncal concealment of certain markers. Dogs were then recorded moving through the calibrated space at a walk and trot. Gait order was identical for all dogs and each test day. Dogs were walked across the testing space at a velocity of 0.9–1.2 m/s and trotted at a velocity of 1.7–2.1 m/s. Each gait was recorded 5 times for analysis. Passes in which the dog visibly changed velocity, turned its head, broke stride, or made any aberrant motions were discarded immediately. The procedure was repeated 5 days after the first in similar fashion, providing a total of 10 trials for analysis.

Kinematic Models

Three distinct models were used to define the canine hind limb, stifle joint rotation center, and kinematics including (1) Sagittal Linear Model, (2) Sagittal Segmental Model, and (3) JCS Model.

Sagittal Linear Model (Figure 2.1A). In this model, the femur was represented by a line connecting the greater trochanter (GT) to the lateral femoral condyle (LFC). The tibia was represented by a line connecting the LFC to the lateral malleolus (LMA). The stifle joint center was defined as the point of articulation between the femoral and tibial segments. The stifle joint

center of rotation was defined as the axis passing through the LFC and perpendicular to the intersecting lines that define the femoral and tibial segments.

Sagittal Segmental Model (Figure 2.1B). Similar to the linear model, the femur was represented by a line connecting GT to LFC; however, the tibia was represented by a line connecting the fibular head (FH) to LMA. The stifle joint center of rotation was defined as the intersection of the 2 segments at the distal aspect of the femoral component and the proximal tibia component. The axis of rotation of the stifle joint was defined as an axis perpendicular to the two segment lines, and passing through the joint center.

Stifle joint angles were calculated by the following equations:

$$\theta_s = \cos^{-1} \frac{\vec{V}_{femur} \cdot \vec{V}_{tibia}}{\left|\vec{V}_{femur}\right|\left|\vec{V}_{tibia}\right|} \quad \text{(Eq. 1)}$$

where the vectors of femur and tibia were defined by position vectors of GT, LFC, and LMA measured from the motion capture system:

$$\vec{V}_{femur} = \vec{V}_{GT} - \vec{V}_{LFC} \quad \text{(Eq. 2)}$$

$$\vec{V}_{tibia} = \vec{V}_{LMA} - \vec{V}_{LFC} \quad \text{(Eq. 3)}$$

In the segmental model, the $\vec{V}_{tibia}$ was defined by substituting $\vec{V}_{LFC}$ by $\vec{V}_{FH}$ in Equation 3.

JCS Method (Figure 2.1C). In this model, the segment of femur and tibia were assumed as a rigid body, and first the local coordinate system (LCS) for each segment was defined by markers attached on the segments during static calibration.

In the femur, the unit vector of z-axis of the LCS was defined by LFC and the medial femoral condyle marker (MFC)

$$\vec{z} = \frac{\vec{V}_{LFC} - \vec{V}_{MFC}}{\left|\vec{V}_{LFC} - \vec{V}_{MFC}\right|} \quad \text{(Eq. 4)}$$

The unit vector of x-axis was defined by a cross product of the vector from LFC to GT and the unit vector of the z- axis

$$\vec{x} = \frac{(\vec{V}_{GT} - \vec{V}_{LFC}) \times \vec{z}}{\left|(\vec{V}_{GT} - \vec{V}_{LFC}) \times \vec{z}\right|} \quad \text{(Eq. 5)}$$

Consequently, the last unit vector of the y-axis was defined by a cross product of two unit vectors of the x- and z- axes

$$\vec{y} = \vec{z} \times \vec{x} \quad \text{(Eq. 6)}$$

The origin of the femoral LCS was set at the GT. In the tibia, the origin for the tibia LCS was at the proximal tibial crest (PTC), and the axes of the LCS were defined in a similar manner to the femoral LCS, in that the z-axis unit vector was defined by the lateral and medial malleolus (LMA and MMA):

$$\vec{z} = \frac{\vec{V}_{LMA} - \vec{V}_{MMA}}{\left|\vec{V}_{LMA} - \vec{V}_{MMA}\right|} \quad \text{(Eq. 7)}$$

And the x-axis unit vector was defined as

$$\vec{x} = \frac{(\vec{V}_{PTC} - \vec{V}_{DTC}) \times \vec{z}}{\left|(\vec{V}_{PTC} - \vec{V}_{DTC}) \times \vec{z}\right|} \quad \text{(Eq. 8)}$$

Where PTC and DTC were the proximal and distal tibial crest markers, and the y-axis unit vector was the same as Equation 6. Three non-orthogonal unit vectors of these axes described joint motion.[2] The JCS flexion/extension angle was converted to a complimentary angle as previously described.[5,13]

Analysis Methods

Waveforms were generated for all 3 models simultaneously during each gait cycle and were compiled graphically, represented with 95% confidence intervals (95% CI). A normalization procedure was then performed on all flexion/ extension waveforms as previously described (Figure 2.2).[6,7,17] These simultaneously collected sagittal waveforms, both pre- and post-normalization, were then compared by GIFA[11] and a Fourier Transformation.[7,17]

GIFA sought to find a set of 1 or more Eigen vectors (in our case, the Eigen vectors contain information concerning differences between gaits), which best distinguished between the means of the measurements, while accounting for variance in the data (i.e., dimensions in which variance is large, are suppressed). The covariance of each statistically significant Eigen vector indicates distinctive differences between the sets of measurements. If no statistically significant Eigen vectors are found, this indicates that no differences were found between the measurements when the overall variance of the measurements was taken into account. Significance was set at P 0.05.

Fourier analysis was performed as described.[7,17] Data for inter-day comparisons was normalized separately for each testing day. Ten Fourier coefficients were used to characterize sagittal stifle joint motion (Table 2.2). Comparison of the Fourier coefficients was accomplished using a repeated measures ANOVA performed by statistical analysis software (SAS v 9.2, Cary, NC). Multiple comparisons were adjusted using Tukey's test. All hypothesis tests were 2-sided and significance was set at P 0.05.

Results

Sagittal flexion and extension waveforms were obtained for each method (Linear, Segmental, and JCS) simultaneously during each gait cycle. In addition, JCS provided data on internal/external and abduction/adduction movement around the stifle joint (Figure 2.2).

Generalized Indicator Function Analysis

Significant intra-dog differences (P 0.05) were found between methods for all dogs (Figure 2.3A and B) at the walk and trot. Significant inter-dog differences (P 0.05) were found between dogs within all methods (Figure 2.4A and B) at both walk and trot. However, when the data were pooled, no significant differences were found between methods in the sagittal waveforms from all dogs at a walk and trot. No inter-day differences existed for all dogs at both a walk and trot. When the data was pooled no inter-day differences were present. Normalization of the data yielded identical results.

Fourier Analysis

Significant intra-dog differences (P o .05) were found between methods for 2 dogs at a trot and 4 dogs at a walk. Significant inter-dog differences (P 0.05) were found between dogs within all methods at both the walk and trot. When the data were pooled, significant differences (P 0.05) were found between methods at a walk and trot (Table 2.2). Significant inter-day differences (P 0.05) were found for all dogs at a walk and trot. Inter-day differences (P 0.05) were also found when the data was pooled (Table 2.2).

After normalization, there were no significant intra-dog differences between methods for all dogs at a trot; however, significant intra-dog differences between methods were found for 2

dogs at a walk. Differences between methods in pooled data were unchanged (Table 2.2). No significant inter-dog differences existed between dogs within all methods at both the walk and trot. Significant inter-day differences were found in 1 dog at a trot and 4 dogs at a walk. Inter-day differences in the pooled data were still present (Table 2.2).

Discussion

We confirmed the use of a skin marker system based on the JCS for collection of canine stifle kinematics.[18] JCS allows acquisition of stifle flexion and extension angles in the sagittal plane, similar to the more traditional sagittal segmental and linear models evaluated, while also providing acquisition of internal/external and abduction/adduction motion around the stifle joint.

Traditionally in veterinary medicine, sagittal flexion/extension angles have been the primary data collected and reported for in vivo dynamic kinematic analysis of canine gait.[5–7,9,19] In this report, a 3-D system was used to obtain sagittal flexion and extension angles from all models (Linear, Segmental, and JCS). The use of a 3-D system for collection of 2-D motion capture has recently been evaluated.[20] In that study, canine flexion and extension angles were collected with a 2-D and 3-D camera system and compared, with the use of a traditional linear marking system. Both systems provided reliable and comparable angular data measurement in the sagittal plane.

Whereas sagittal plane evaluation provides an easy assessment of flexion and extension, it greatly limits the evaluation of true joint motion and under utilizes the 3-D camera systems, if only used for evaluation of flexion and extension. Because joint motion occurs in 3-D, an inability to assess movement in these additional dimensions hinders our understanding of both normal and pathologic joint motion. Previous in vivo studies have evaluated canine kinematics in

pathologic joints; however, these studies have reported changes in the flexion/extension angle.[4,5,19] The use of the JCS marking system allowed evaluation of sagittal plane stifle motion, similar to traditional linear and segmental models, while providing information on internal/external and abduction/adduction angular motion. Three-dimensional kinematic evaluations of normal and cranial cruciate deficient canine stifles confirm that joint motion is augmented in > 1 plane after cranial cruciate ligament rupture (CCLR).[21–23] It has been proposed that restoration of normal 3-D stifle motion as determined by stifle kinematics may need to be considered in evaluating surgical treatment modalities for CCLR.[21] To date, much of the information regarding 3-D changes after CCLR has been provided by cadaveric or invasive in vivo methods of data collection—which are not applicable in the clinical setting.[21–23] The JCS method evaluated in this study provides a means to evaluate 3-D stifle motion in a non-invasive and clinically feasible manner.

Fourier analysis has been used in earlier studies of canine gait.[4,5,7] Previously, these reports limited the analysis to the essential coefficients, defined as the coefficients needed to reconstruct ≥95% of the waveform. The number of essential coefficients needed to characterize the stifle joint angle varied in these studies. The first 5 coefficients[7] were used at a walk, and 3 coefficients[4,5] at a trot. In our study, determination of essential coefficients was not performed and all 10 coefficients produced were used to characterize the stifle flexion and extension angle at the walk and the trot. Notably, significant differences were found within the first 6 coefficients of the original data for both the walk and trot. Within the normalized data, significant differences extended to 5 coefficients for the walk and 7 for the trot. These results identify detectable differences beyond the previously established essential coefficients.[4,5,7] This additional data may provide valuable comparative information; however, further study is warranted before any

conclusions can be gleaned regarding the inclusion or exclusion of non-‘‘essential’’ coefficients and the resulting affect on overall analysis.

Normalization of the sagittal waveform data were performed in this report. Previous reports have documented a shift in gait waveforms along the vertical axis secondary to differences in marker placement.[6–8,24] In an attempt to decrease the affect of this shift on analysis, normalization procedures were implemented in these reports. Normalization of the data seeks to decrease this shift and reduce a substantial source of variability that may not represent true temporal changes in the waveform, and thus true differences in movement.

Comparison between analysis methodologies proved valuable. Both GIFA and Fourier analysis were able to detect differences between methods; however, unlike GIFA, analysis of the Fourier coefficients was altered by the normalization process. Fourier analysis is affected by the position of the waveform along the vertical axis.[4,6,7,24] Therefore, after normalization, less variability existed among the studied waveforms. Alternatively, GIFA compares the waveform shape and is unaffected by the position along the vertical axis. Interestingly, while individual comparisons were altered by normalization, comparison of the pooled data was unaffected.

Limiting the influence of waveform position on analysis methodology may prove valuable when data collection will occur at multiple time points. In this study, GIFA analysis found no significant differences between the waveform shapes of dogs between testing days. Examination of this same data with Fourier analysis yielded differing results. It found significant differences between testing days in all dogs; however, after normalization those differences were diminished for both the individual and pooled data. This suggests that when comparing normal dog gaits from multiple testing sessions, while inter-day variation may occur, waveform shape remains consistent between testing days.

The differences between methods detected with GIFA were attributed to the variations in marker locations used to establish the models and joint center definitions associated with the corresponding models. Historically, the canine stifle joint center has commonly been established as the midpoint between the LFC and the FH, in linear models.[4–7,9,19] That demarcation was not used in our study as that marker location was not uniformly represented in all 3 models tested, and therefore would not allow simultaneous data collection. As a result, the LFC was used to represent the stifle joint center in the linear model (Figure 2.1A), similar to previous studies.[25–27] The joint center in the segmental model used the point of bisection between the femoral and tibial segment, at approximately the area between the LFC and the FH (Figure 2.1B); however, the JCS model (Figure 2.1C) does not use a traditional joint center, like the linear and segmental models. Instead all rotations are described by the relative relationship between the defined femoral and tibial axes. Therefore, because rotation occurs around a fixed axis, the center of rotation could be most aptly described as a point located in the center of the MFC and LFC. Even with these inter-model differences, the general waveforms generated from each model were equivocal. Thus, while model methodology provided for some waveform variability, all 3 methods produced similar flexion/extension waveforms. These results are consistent with previous kinematic studies of the canine stifle.[22,23] Interestingly, while GIFA identified individual differences, when all dog gaits were combined no significant difference existed between measurement methods. The implication of these results is that, although on a one-by-one comparison level the methods may differ in a consistent way, the overall variance in large sets of dog gaits masks any consistent differences in measurement methods, at the population level. The same cannot be stated for Fourier analysis, which found differences on the individual and population levels.

Efforts were made to alleviate sources of experimental error. All dogs were gaited by 1 handler (A.S.). Additionally, in an attempt to limit variations in marker placement between dogs on the 2 testing days, markers were placed on the dogs by only 1 person (J.P.). This was kept consistent throughout the study. Despite this, some variation in marker placement did occur between dogs on the 2 collection days as is evident by the Fourier analysis. While all markers were secured and no detachment occurred, any loss of markers requiring reattachment would have resulted in recollection of all trials on that day. The use of skin markers and the accuracy of a skin marker system for non-invasive kinematic evaluation of joint motion has been a source of controversy in gait analysis. Ideally, for accurate evaluation of joint motion the markers delineating the targeted bones should be rigidly affixed to the skeletal system so as to provide precise representations of bone motion. However, rigid fixation techniques currently require invasive measures and long surgical recovery times before data collection that are not conducive to applications in the clinical setting.[22,28] Unfortunately, to date no direct comparison between rigidly affixed and skin markers for kinematic evaluation in dogs has been evaluated. The major concern with skin marker systems is primarily marker motion secondary to soft tissue movement artifact.[5,17] A previously published investigation into marker motion with a similar marking and collection system used in this study detected marker movement of 2 mm and revealed > 2% marker movement during a complete dynamic gait cycle for both the femoral and tibial markers.[13] While these data do not account for movement of a particular marker relative to its assigned anatomic site, it does document minimal movement between markers.

Our study hypotheses were accepted. Each model provided useful and repeatable flexion–extension data; however, only the JCS provided data from the additional axes. It was not surprising that these 3 measurement methodologies provided similar results, as they were

collected simultaneously in the dogs. It was also not unexpected to see subtle but significant differences in these sagittal flexion–extension waveforms because of the different markers used to create the models. Additionally, in regard to waveform analysis, both GIFA and Fourier analysis provided the ability to assess differences in waveforms. Unlike the Fourier analysis in this study, which only assesses if the waveforms are similar or dissimilar, GIFA gives rise to Eigen vectors that are functions of time and therefore may prove beneficial in temporally isolating gait differences. This may also allow for a sensitive measure of variability between gait waveforms in which only fine timing differences occur.

References

1. Gillette RL, Angle TC: Recent developments in canine locomotor analysis: a review. Vet J 2008;178:165–176

2. Grood ES, Suntay WJ: A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J Biomech Eng 1983;105:136–144

3. Bockstahler BA, Henninger W, Muller M, et al: Influence of borderline hip dysplasia on joint kinematics of clinically sound Belgian Shepherd dogs. Am J Vet Res 2007;68:271–276

4. Bennett RL, DeCamp CE, Flo GL, et al: Kinematic gait analysis in dogs with hip dysplasia. Am J Vet Res 1996;57: 966–971

5. DeCamp CE, Riggs CM, Olivier NB, et al: Kinematic evaluation of gait in dogs with cranial cruciate ligament rupture. Am J Vet Res 1996;57:120–126

6. DeCamp CE, Soutas-Little RW, Hauptman J, et al: Kinematic gait analysis of the trot in healthy greyhounds. Am J Vet Res 1993;54:627–634

7. Hottinger HA, DeCamp CE, Olivier NB, et al: Noninvasive kinematic analysis of the walk in healthy large-breed dogs. Am J Vet Res 1996;57:381–388

8. Allen K, DeCamp C, Braden T, et al: Kinematic gait analysis of the trot in healthy mixed breed dogs. Vet Compend Orthop Trauma 1994;7:148–153

9. Schaefer SL, DeCamp CE, Hauptman JG, et al: Kinematic gait analysis of hind limb symmetry in dogs at the trot. Am J Vet Res 1998;59:680–685

10. Williams GE, Silverman BW, Wilson AM, et al: Disease specific changes in equine ground reaction force data documented by use of principal component analysis. Am J Vet Res 1999;60:549–555

11. Yokoo T, Knight BW, Sirovich L: An optimization approach to signal extraction from noisy multivariate data. Neuroimage 2001;14:1309–1326

12. Wu G, Cavanagh PR: ISB recommendations for standardization in the reporting of kinematic data. J Biomech 1995;28:1257–1261

13. Budsberg SC, Verstraete MC, Reynolds LR, et al: Three-dimensional non-invasive kinematics of the Canine Stifle. Vet Surg 1999;28:387–388

14. Winter DA: Biomechanics and Motor Control of Human Movement (ed 3). Hoboken, NJ, John Wiley & Sons, 2005, pp 183–186

15. Lu TW, O'Connor JJ: A three-dimensional computer graphics-based animated model of the human locomotor system with anatomical joint constraints. J Biomech 1998;31:116

16. Veldpaus FE, Woltring HJ, Dortmans LJ: A least-squares algorithm for the equiform transformation from spatial marker coordinates. J Biomech 1988;21:45–54

17. DeCamp CE: Kinetic and kinematic gait analysis and the assessment of lameness in the dog. Vet Clin North Am Small Anim Pract 1997;27:825–840

18. Torres BT, Punke JP, Fu Y, et al: Comparison of three dimensional kinematic data gathered by the joint coordinate system modeling of the canine stifle with linear and limb segmental models. Vet Surg 2008 37: E5 (abstract)

19. Marsolais GS, McLean S, Derrick T, et al: Kinematic analysis of the hind limb during swimming and walking in healthy dogs and dogs with surgically corrected cranial cruciate ligament rupture. J Am Vet Med Assoc 2003;222: 739–743

20. Kim J, Rietdyk S, Breur GJ: Comparison of two-dimensional and three-dimensional systems for kinematic analysis of the sagittal motion of canine hind limbs during walking. Am J Vet Res 2008;69:1116–1122

21. Chailleux N, Lussier B, De Guise J, et al: In vitro 3-dimensional kinematic evaluation of 2 corrective operations for cranial cruciate ligament-deficient stifle. Can J Vet Res 2007;71:175–180

22. Korvick DL, Pijanowski GJ, Schaeffer DJ: Three-dimensional kinematics of the intact and cranial cruciate ligament-deficient stifle of dogs. J Biomech 1994;27:77–87

23. Tashman S, Anderst W, Kolowich P, et al: Kinematics of the ACL-deficient canine knee during gait: serial changes over two years. J Orthop Res 2004;22:931–941

24. Kadaba MP, Ramakrishnan HK, Wootten ME, et al: Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. J Orthop Res 1989;7:849–860

25. Lee JY, Kim G, Kim JH, et al: Kinematic gait analysis of the hind limb after tibial plateau levelling osteotomy and cranial tibial wedge osteotomy in ten dogs. J Vet Med A Physiol Pathol Clin Med 2007;54:579–584

26. Marghitu DB, Kincaid SA, Rumph PF: Nonlinear dynamics stability measurements of locomotion in healthy greyhounds. Am J Vet Res 1996;57:1529–1535

27. Marghitu DB, Nalluri P: An analysis of greyhound gait using wavelets. J Electromyogr Kinesiol 1997;7:203–212

28. Taylor WR, Ehrig RM, Duda GN, et al: On the influence of soft tissue coverage in the determination of bone kinematics using skin markers. J Orthop Res 2005;23:726–734

Table 2.1. Marker locations for Joint Coordinate System Kinematic Modeling of a Canine Stifle Unilaterally

Femoral Markers	Tibial Markers
Greater trochanter (GT)	Fibular head (FH)
Craniolateral aspect of the quadriceps muscle	Proximal aspect of tibial crest (PTC)*
Lateral femoral condyle (LFC)	Distal aspect of tibial crest (DTC)*
Medial femoral condyle (MFC)*	Junction of gastrocnemius muscle and tendon
	Medial malleolus (MMA)*
	Lateral malleolus (LMA)

*Markers that are removed during the acquisition of dynamic trials.

Table 2.2. Mean Fourier Coefficients from All Methods for the Sagittal Femorotibial Joint Angle in all Dogs at a Walk and Trot

	Original							Normalized					
	Trot			Walk				Trot			Walk		
	JCS	SEG	LIN	JCS	SEG	LIN		JCS	SEG	LIN	JCS	SEG	LIN
A1	5.45	5.38	5.02	1.95	1.98	1.83	A1	5.44	5.36	5.00	1.92	1.94	1.80
A2	2.74	2.88	2.70	2.97†‡	3.15†‡	2.87†‡	A2	2.74	2.88	2.70	3.00†‡	3.18†‡	2.89†‡
A3	0.06	0.11	0.11	0.76‡	0.83‡	0.79‡	A3	0.05	0.11	0.11	0.75‡	0.82‡	0.79‡
A4	−0.12‡	−0.11‡	−0.09‡	0.02	0.03	0.04	A4	−0.12‡	−0.11‡	−0.09‡	0.02	0.03	0.04
A5	−0.04	−0.04	−0.03	−0.03	−0.02	−0.02	A5	−0.04	−0.04	−0.03	−0.03	−0.02	−0.02
A6	−0.02‡	−0.02‡	−0.02‡	−0.04	−0.04	−0.03	A6	−0.02‡	−0.02‡	−0.02‡	−0.04	−0.04	−0.03
A7	−0.01	−0.02	−0.01	−0.02	−0.02	−0.02	A7	−0.01‡	−0.02‡	−0.01‡	−0.02	−0.02	−0.02
A8	−0.01	−0.01	−0.01	−0.01	−0.02	−0.02	A8	−0.01	−0.01	−0.01	−0.01	−0.02	−0.02
A9	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	A9	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01
A10	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	A10	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01
B1	5.81*‡	6.34*‡	5.86*‡	5.38†‡	5.45†‡	5.10†‡	B1	5.83*‡	6.36*‡	5.88*‡	5.41†‡	5.48†‡	5.12†‡
B2	−1.42	−1.38	−1.24	0.47	0.65	0.54	B2	−1.43	−1.39	−1.25	0.47	0.65	0.54
B3	−0.44	−0.52	−0.48	−0.89	−0.89	−0.79	B3	−0.44	−0.52	−0.48	−0.90	−0.89	−0.78
B4	−0.06	−0.08	−0.07	−0.20‡	−0.21‡	−0.19‡	B4	−0.06	−0.08	−0.07	−0.20	−0.20	−0.18
B5	0.00	−0.02	−0.02	−0.06‡	−0.07‡	−0.06‡	B5	0.00	−0.02	−0.02	−0.06‡	−0.07‡	−0.06‡
B6	−0.01	−0.02	−0.02	−0.02‡	−0.03‡	−0.02‡	B6	−0.01	−0.02	−0.02	−0.02	−0.03	−0.02
B7	−0.01	−0.02	−0.02	−0.01	−0.02	−0.01	B7	−0.01	−0.02	−0.02	−0.01	−0.01	−0.01
B8	−0.01	−0.02	−0.02	−0.01	−0.02	−0.01	B8	−0.01	−0.02	−0.02	−0.01	−0.02	−0.01
B9	−0.01	−0.02	−0.02	−0.01	−0.01	−0.01	B9	−0.01	−0.02	−0.02	−0.01	−0.01	−0.01
B10	−0.01	−0.02	−0.01	−0.01	−0.01	−0.01	B10	−0.01	−0.02	−0.01	−0.01	−0.01	−0.01

Coefficients from the original and normalized waveforms are depicted. A1–A10, cosine coefficients; B1–B10, sine coefficients.
*Significant differences between methods for trot.
†Significant differences between methods for walk.
‡Significant inter-day differences between methods for the walk or trot.

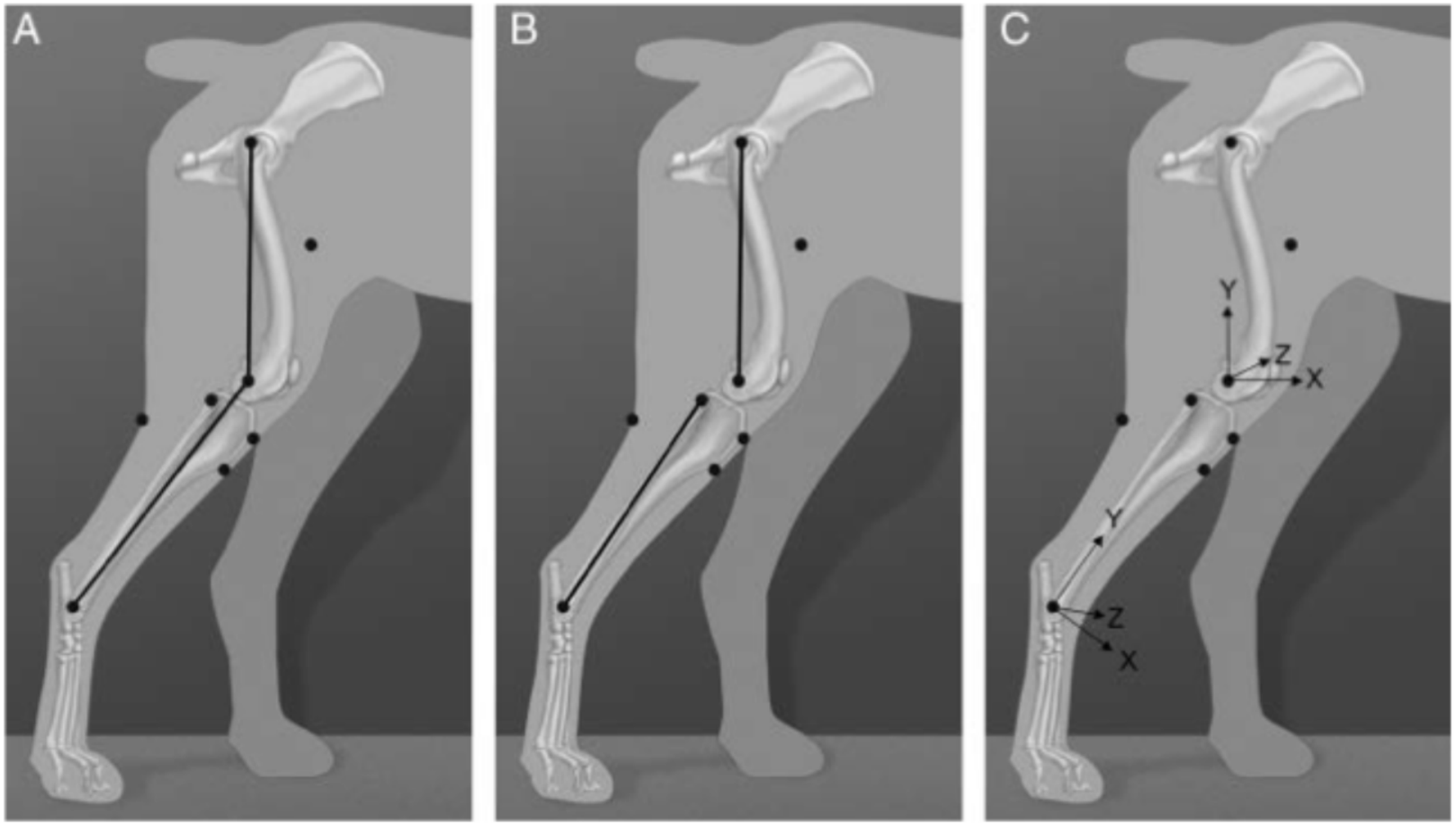


Figure 2.1. Illustrative representation of the body segments and kinematic marker placement on the skin of the canine hind limb. (A) Sagittal Linear Model, (B) Sagittal Segmental Model, (C) Joint Coordinate System Model.

Figure 2.2. Graphs of mean stifle flexion and extension angles for all dogs at a walk and a trot with all 3 methods illustrated. Original and Normalized waveforms are depicted. After normalization the variance was diminished as is evident by the change in the 95% confidence interval (95% CI) between pre- and postnormalization flexion and extension waveforms. Quantitative angular change is indicated by the appropriate waveform with 95% CI. Internal/external and abduction/adduction angles were acquired only by the Joint Coordinate System (JCS).

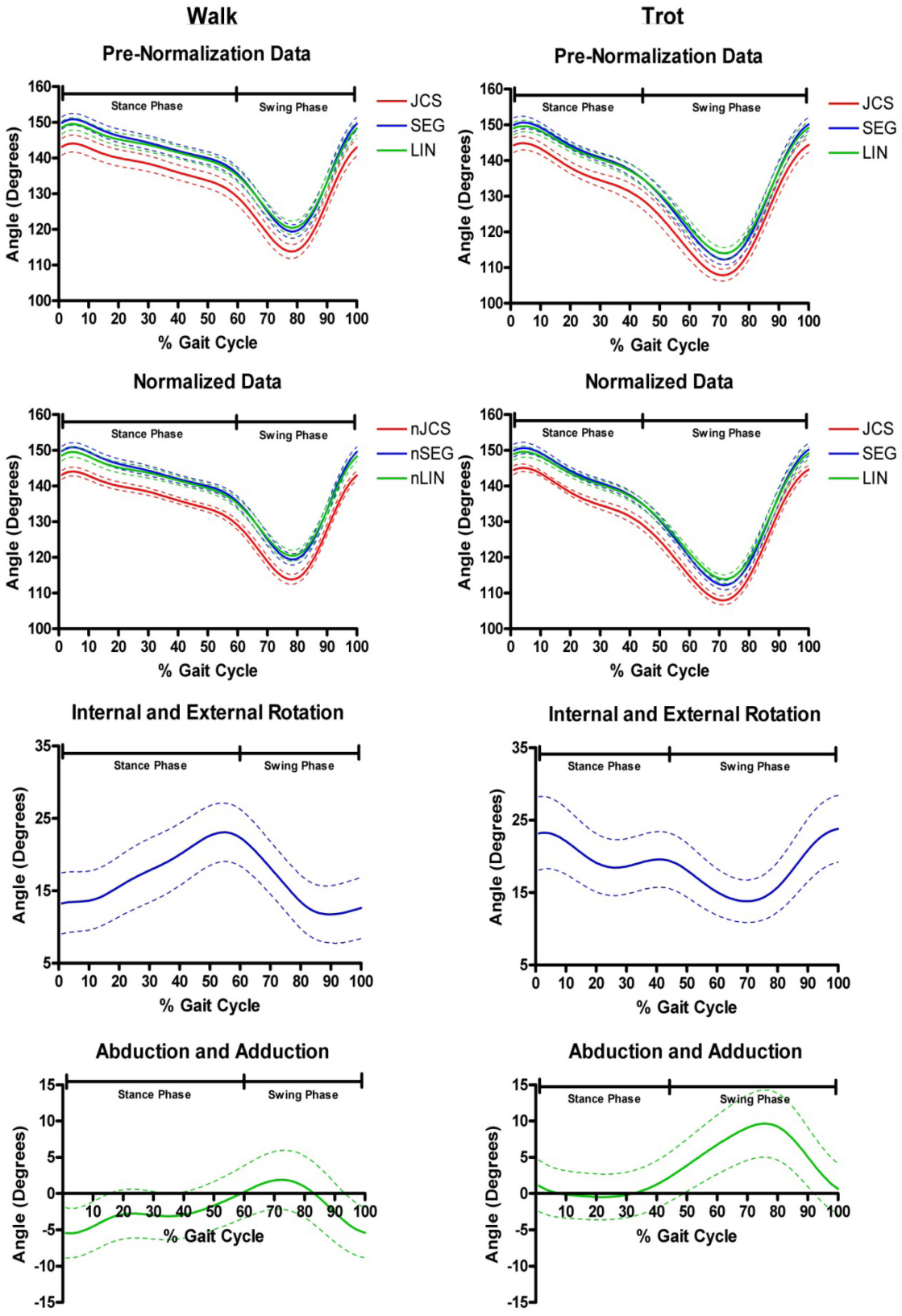
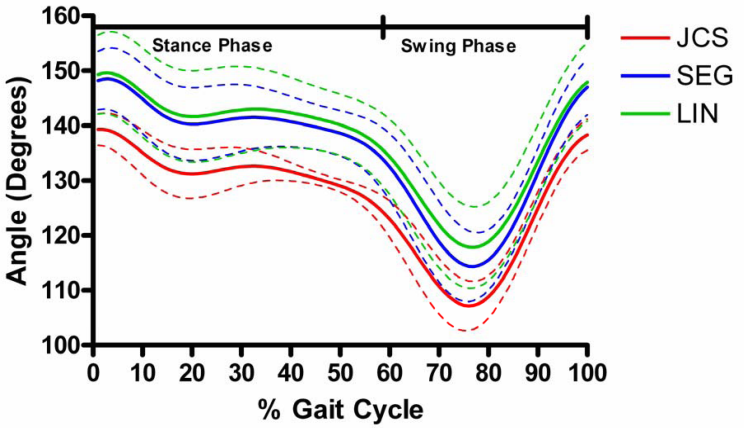
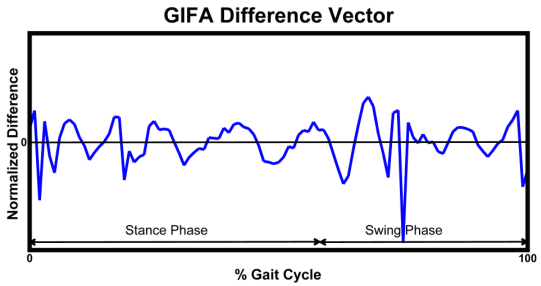
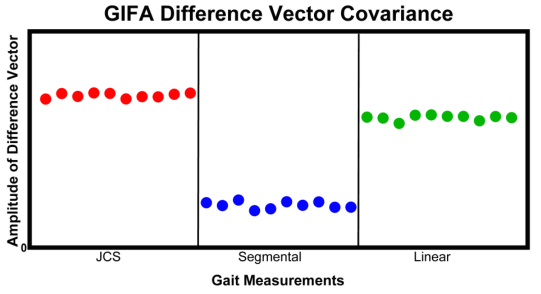

Walk
Pre-Normalization Data
Stance Phase
Swing Phase
JCS
SEG
LIN
Angle (Degrees)
% Gait Cycle
Trot
Pre-Normalization Data
Normalized Data
nJCS
nSEG
nLIN
Internal and External Rotation
Abduction and Adduction

Figure 2.3. Mean stifle flexion and extension angle at a walk (A) and trot (B) with 95% confidence intervals for an individual dog measured with differing methods. Significant differences, as illustrated by this comparison between methods for an individual dog, were found for all individual dogs between methods at both a walk and trot. The temporal differences between methods are indicated by the generalized indicator function analysis (GIFA) Difference Vector plot. GIFA produces a multidimensional vector representing the most significant difference between the groups being compared. For illustrative purposes this vector is depicted on the graph as a waveform corresponding to the temporal differences between gaits. Changes in amplitude away from baseline [0] correspond to the degree of difference detected between groups. However, the establishing vector is unitless and therefore the direction of waveform movement along the vertical axis, away from baseline [0], is arbitrary. The GIFA Difference Vector Covariance plot depicts a statistically significant change between methods. Each (□) represents an individual trial. Small movements along the vertical axes within a method indicate slight variation between individual trials within that method. Differences in vertical axes position between the groups (LIN, JCS, and SEG) indicate significant differences between groups. The distance between the groups along the vertical axes denotes the degree of difference between them. The actual position of the groups along the vertical axis represents a relative quantity. LIN, Sagittal Linear Model; SEG, Sagittal Segmental Model; JCS, Joint Coordinate System Model.

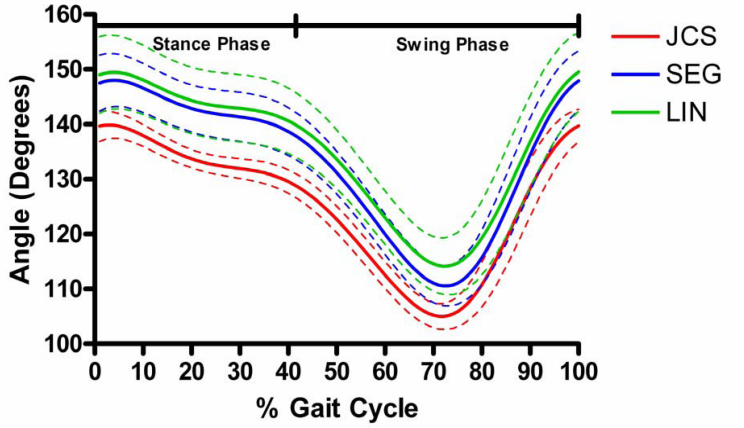
A

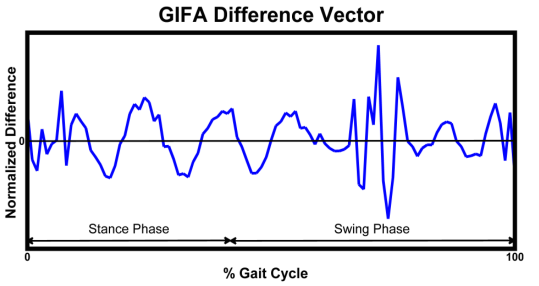

Stance Phase
Swing Phase
JCS
SEG
LIN
Angle (Degrees)
% Gait Cycle


GIFA Difference Vector
Normalized Difference
Stance Phase
Swing Phase
% Gait Cycle


GIFA Difference Vector Covariance
Amplitude of Difference Vector
JCS
Segmental
Linear
Gait Measurements

B


Stance Phase
Swing Phase
JCS
SEG
LIN
Angle (Degrees)
% Gait Cycle


GIFA Difference Vector
Normalized Difference
Stance Phase
Swing Phase
% Gait Cycle

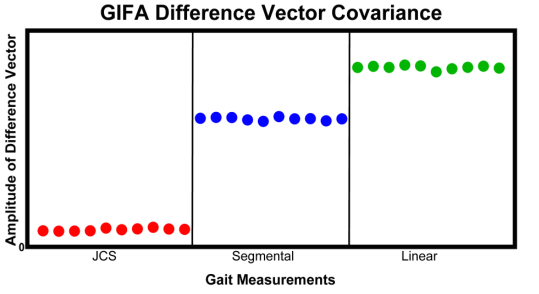
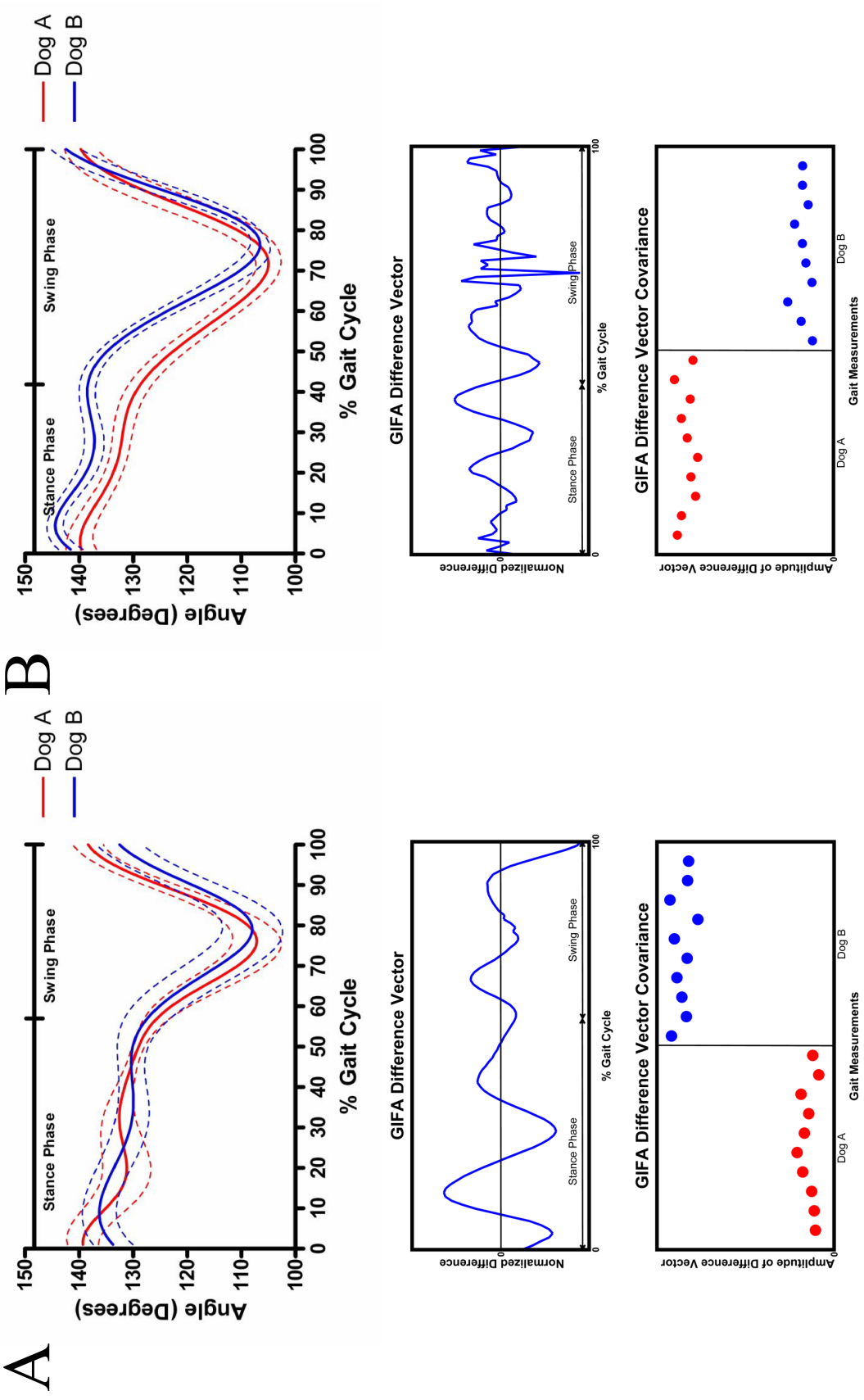

GIFA Difference Vector Covariance
Amplitude of Difference Vector
JCS
Segmental
Linear
Gait Measurements

Figure 2.4. Mean stifle flexion and extension angle at a walk and trot with 95% confidence intervals of two different dogs. Significant differences, as illustrated by this typical comparison of two different dogs, were found between all individual dogs at a walk and trot. (A) For the walk, the generalized indicator function analysis (GIFA) Difference Vector plot illustrates temporal differences of a relatively low frequency, as indicated by a smooth waveform. This is due to fine differences in the timing of maximal extension. (B) For the trot, the GIFA Difference Vector plot illustrates temporal changes of a comparatively higher frequency as indicated by a less smooth waveform. The majority of these high-frequency differences occur at the time of maximal extension. The GIFA Difference Vector Covariance plots for both the walk and trot depict significant differences between Dog A and Dog B.


A
B
Dog A
Dog B
Angle (Degrees)
% Gait Cycle
Stance Phase
Swing Phase
GIFA Difference Vector
Normalized Difference
GIFA Difference Vector Covariance
Amplitude of Difference Vector
Gait Measurements

CHAPTER 3

THE EFFECT OF MARKER LOCATION VARIABILITY ON NONINVASIVE CANINE STIFLE KINEMATICS[1]

[1]Torres B.T., Whitlock D., Reynolds L.R., Fu Y.C., Navik J.A., Speas A.L., Sornborger A., and Budsberg S.C. 2011. *Veterinary Surgery.* 40.6: 715-719. Reprinted here with permission of publisher.

Abstract

Objective: Evaluate the effect of marker placement on kinematics of the canine stifle in 3 distinct hindlimb models.

Study Design: In vivo biomechanical study.

Animals: Normal adult mixed-breed dogs (n=5).

Methods: Ten retroreflective markers were affixed to the skin on the right rear leg of each dog to establish normal stifle kinematics. Four additional markers were placed around the greater trochanter (GT), 2 cm cranial, caudal, dorsal, and ventral to evaluate single marker placement variability on kinematic model data. Dogs were walked and trotted 5 times through the calibrated space. Sagittal flexion and extension angle waveforms were acquired during each trial with 3 models that were produced simultaneously during each gait. The GT marker was reassigned to 1 of the 4 additional locations (cranial, caudal, dorsal, and ventral) to alter the kinematic model. Comparison of sagittal flexion and extension angle waveforms was performed with Generalized Indicator Function Analysis.

Results: Each model provided consistent equivalent sagittal flexion–extension data. Analysis revealed statistically significant differences between all GT locations. The differences were greatest in the cranial and caudal locations for all models.

Conclusion: Deviation of the GT marker in the cranial/caudal direction from an anatomically normal position produces a greater degree of difference than deviation in a dorsal/ventral direction.

Introduction

The use of superficial skin markers is currently the most widely reported method of in vivo kinematic data acquisition in veterinary medicine.[1–8] Previous reports have elucidated the effect of asymmetric marker placement in a bilateral model[9] as well as on kinematic waveform data in unilateral models.[1,3–6] These reports have demonstrated that inconsistent marker placement can produce disparities in flexion and extension joint angles. However, the effect of marker placement errors in specific directions has not been reported.

Our purpose was to evaluate the effect of marker placement on 3-dimensional kinematics of the canine stifle with the use of 3 distinct marking systems.[10] Our hypotheses were that marker placement error of a single marker during dynamic gait testing will result in detectable differences in gait data. Also, those errors in the horizontal plane (cranial and caudal marker location) will result in a greater degree of difference than errors in the vertical plane (dorsal and ventral marker location).

Materials And Methods

Animals

Five adult mixed-breed dogs weighing 20–30kg from an established research colony were studied. All dogs were ~5 years of age. All dogs had normal bilateral hip and stifle radiographs with no detectable pathologic changes. Force plate analysis (peak vertical force and vertical impulse), CBC, serum chemistry, and complete physical exams were performed before initiation of the study and were all normal. Dogs were housed indoors in a climate controlled environment and feed commercially available dog food ad libitum.

Motion Collection

Fifteen spherical retroreflective markers (8 mm in diameter) were used to produce all the models evaluated (Table 3.1). Ten markers were affixed with double-sided tape and cyanoacrylate to the right rear leg. Four additional markers, attached similarly, were placed at a distance of 2 cm around the greater trochanter (GT) marker at a cranial, caudal, dorsal, and ventral position. These markers were used to mimic marker placement error. One lateral toe (metatarsophalangeal joint) was utilized to establish gait cycle.

All markers were applied by only 1 person throughout the study. All markers were secured and no detachment occurred. Any loss of markers requiring reattachment would have resulted in recollection of all trials for that dog on that day.

A 3-dimensional testing space was established on a 13 m walkway. Right-handed orthogonal coordinate axes were used to describe the testing space in 3 dimensions with 0,0,0 (X,Y,Z) located in the center of the testing space. Before each day's collection, the system was calibrated with a calibration frame (Vicon Peak Motus L-Frame, Vicon- Peak, Centennial, CO) of known dimensions and by dynamic linearization with a custom made 0.700 m wand. Marker locations were captured by a kinematic system of 8 infrared cameras (Vicon MX03, Vicon Motion Systems, Los Angeles, CA) arranged around the gait platform. Data was captured at 200 Hz and then recorded and analyzed by a motion-analysis program (Peak Motus 9.2, Vicon Motion Systems).

Initially, a static or anatomic trial of each dog was collected, as described previously.[10] Four markers (noted by an asterisk in Table 1) were removed during subsequent dynamic trials. These markers were reconstructed from the static or anatomic trial and were used as virtual markers during the dynamic trials, as described previously.[11,12] Dogs were then recorded moving

through the calibrated space at a walk and trot. The order each gait was performed was identical for all dogs. Dogs were walked across the testing space at a velocity between 0.9 and 1.2 m/s and trotted at a velocity between 1.7 and 2.1 m/s. Each gait was recorded 5 times for analysis. Passes in which the dog visibly changed velocity, turned its head, broke stride, or made any aberrant motions were discarded immediately. All dogs were gaited by the same handler.

Kinematic Models

Three distinct models were used to define the canine hind limb, stifle joint rotation center, and kinematics including (1) Sagittal Linear Model (LIN), (2) Sagittal Segmental Model (SEG), and (3) Joint Coordinate System (JCS) Model as illustrated in Figure 3.1. These models were used as described previously.[10]

Sagittal flexion and extension angles were obtained simultaneously for all 3 methods (LIN, SEG, JCS). For each method, the GT marker was reassigned in each individual trial to a cranial, caudal, ventral, and dorsal position within the motion analysis program to establish the new femoral segment in those respective positions. This reassignment of the GT marker within the motion analysis software allowed for the production of 5 different, yet simultaneously collected data sets for each individual trial as illustrated in Figure 3.2. Therefore, each normal individual trial and the corresponding variants (cranial, caudal, dorsal, ventral) differed by only the location of the GT. The JCS method additionally provided internal/external rotation and abduction/adduction angles for all 5 GT locations. The sagittal flexion and extension waveforms for each of the 3 models (LIN, SEG, JCS) were then analyzed.

Analysis Methods

Waveforms were generated for all 3 models and GT locations simultaneously during each gait cycle, and were compiled graphically (Figure 3.2). These simultaneously collected sagittal waveforms were compared by Generalized Indicator Function Analysis (GIFA), as described previously.[10,13] Significance was set at $P < 0.05$.

Results

Sagittal flexion and extension angles were obtained simultaneously for all 3 methods (LIN, SEG, JCS). No marker detachment occurred.

Each GT marker location (normal, cranial, caudal, dorsal, ventral) produced visually similar waveform shapes. However the cranial, caudal, dorsal, and ventral GT locations resulted in a ‘‘shifting’’ of the waveform away from normal, up or down along the y-axis. The greatest shift from normal was seen in the cranial and caudal GT marker locations (Figure 3.2).

Significant differences ($P<.05$) were found between methods (LIN, SEG, JCS) for all dogs in each of the 5 GT locations (normal, cranial, caudal, dorsal, ventral), at a walk and trot. The degree of difference between models was greatest between the JCS and each of the 2 remaining models (SEG, LIN).

Significant differences ($P<.05$) were found between all locations (normal, cranial, caudal, dorsal, ventral) for all dogs within each of the 3 models (LIN, SEG, JCS), at both a walk and trot. In all 3 models, the degree of difference compared with normal was greatest for the cranial and caudal markers and less for the dorsal and ventral markers at both the walk and trot (Figure 3.3).

Discussion

Marker placement has been shown to influence kinematic analysis by altering the gait cycle waveform.[4,5,14,15] Therefore, evaluating the effect of marker placement variability on canine kinematics is important in establishing and critically evaluating gait data.

In this study, a population of mixed-breed dogs was used. Previous studies have focused on the evaluation of specific breeds.[2,4,16] We elected to evaluate a more heterogeneous population to more closely resemble what would be encountered in a clinical setting.

The GT was chosen to evaluate the effect of marker placement on kinematics in this study. This marker is a shared marker location for all models (LIN, SEG, JCS) in the study and provides for an accurate assessment between and within them. Additionally, the GT is a universally used marker location in veterinary hindlimb kinematics and has generous soft tissue coverage; therefore, allowing for the greatest chance of erroneous placement in the commonly used models of canine sagittal plane kinematics.[1,3–6,10,17]

Analysis of the sagittal flexion and extension angles revealed differences between each marker location (normal, cranial, caudal, dorsal, and ventral). The different locations affected each model (LIN, SEG, JCS) similarly. Interestingly, the most significant degree of difference occurred in the cranial and caudal positions, while dorsal and ventral marker locations revealed a lesser degree of difference from the anatomically normal position (Figures 3.2 and 3.3). This indicates that whereas marker placement errors produce statistically significant differences, errors in the cranial and caudal directions produce a greater degree of difference than errors in the dorsal and ventral direction.

Waveform shapes were similar for all GT locations in all models (LIN, SEG, JCS). However, while the normal, dorsal, and ventral marker locations for all models (LIN, SEG, JCS)

are tightly clustered along the y-axis, the cranial and caudal locations produced waveforms that were translated a greater distance away from normal (Figure 3.3). This is secondary to greater angular changes produced in the sagittal plane at the cranial and caudal locations. The cranial location produces a more obtuse stifle angle while the caudal location produces a more acute angle.

These data support previous reports of kinematic gait waveform translocation along the vertical axes secondary to marker placement.[4,9,14] A normalization procedure has been shown to be effective at minimizing this shifting along the vertical axis.[4,5] These reports implemented Fourier Analysis (FA) for comparative assessment. Analysis methodologies such as FA are affected by differences in waveform position and therefore may benefit from normalization. However, GIFA analysis is a methodology that compares differences between waveform shapes and the position on the y-axis is unimportant.[10] Interestingly, because GIFA is unaffected by waveform position these data also indicate that marker location affects the overall waveform shape. The clinical relevance of this has yet to be discerned.

These data elucidate the concern with reapplication of markers for intraday testing. Whereas visually similar waveform shapes were attained, variability was detected by GIFA. Furthermore, overall angular measurement can vary as is evident by the shifting along the vertical axis. This may prove most important when singular point data is utilized for analysis purposes. Therefore, great care should be taken to provide for secure attachment of all markers to prevent the need for reapplication during testing. Unfortunately, from this data we can only assert this concern regarding reapplication of the GT marker. The effect of multiple marker reapplication or variation was not evaluated in this study.

All efforts were made to limit experimental error. It is possible that some variations in marker placement may have occurred between dogs. In an attempt to decrease this, markers were applied by only 1 person throughout the study. While all markers were secured and no detachment occurred, any loss of markers requiring reattachment would have resulted in recollection of all trials for that dog on that day. Also, all dogs were gaited by the same handler. Additionally, the use of superficial skin markers for the evaluation of joint motion has been a source of controversy. The major concern with skin marker systems is primarily marker motion secondary to soft tissue movement artifact.[3,18] However, in this study, with the exception of GT marker reassignment, all marker data was simultaneously collected and identical. Therefore, for comparison and analysis purposes any variability attributable to marker motion was uniform for all trials.

A limitation to this study was the evaluation of only 1 marker. The use of a solitary marker allowed for the evaluation of isolated directional motion of markers. However, no information regarding other markers can be gleaned from this data. It is expected that similar results would have been obtained from identical testing of the lateral malleolar marker, because of the mirror-image location. However the limited soft tissue coverage in that area makes errors of similar magnitude, especially in the cranial and caudal direction unattainable and unexpected in a clinical setting.

The hypotheses in this study were accepted. Simulated marker placement error resulted in detectable differences in gait data. Errors in the horizontal plane (cranial and caudal marker location) resulted in a greater degree of difference than errors in the vertical plane (dorsal and ventral marker location) in this stifle kinematic collection protocol. Additionally, errors in the

horizontal plane produced the greatest shift along the y-axis as compared with the anatomically normal position.

References

1. Bennett RL, DeCamp CE, Flo GL, et al: Kinematic gait analysis in dogs with hip dysplasia. Am J Vet Res 1996;57:966–971

2. Bockstahler BA, Henninger W, Muller M, et al: Influence of borderline hip dysplasia on joint kinematics of clinically sound Belgian Shepherd dogs. Am J Vet Res 2007;68: 271–276

3. DeCamp CE, Riggs CM, Olivier NB, et al: Kinematic evaluation of gait in dogs with cranial cruciate ligament rupture. Am J Vet Res 1996;57:120–126

4. DeCamp CE, Soutas-Little RW, Hauptman J, et al: Kinematic gait analysis of the trot in healthy greyhounds. Am J Vet Res 1993;54:627–634

5. Hottinger HA, DeCamp CE, Olivier NB, et al: Noninvasive kinematic analysis of the walk in healthy large-breed dogs. Am J Vet Res 1996;57:381–388

6. Colborne GR, Innes JF, Comerford EJ, et al: Distribution of power across the hind limb joints in Labrador Retrievers and Greyhounds. Am J Vet Res 2005;66:1563–1571

7. Bennett D, Ogonda L, Elliott D, et al: Comparison of gait kinematics in patients receiving minimally invasive and traditional hip replacement surgery: a prospective blinded study. Gait Posture 2006;23:374–382

8. Marsolais GS, McLean S, Derrick T, et al: Kinematic analysis of the hind limb during swimming and walking in healthy dogs and dogs with surgically corrected cranial cruciate ligament rupture. J Am Vet Med Assoc 2003;222:739–743

9. Audigie F, Pourcelot P, Degueurce C, et al: Asymmetry in placement of bilateral skin markers on horses and effects of asymmetric skin marker placement on kinematic variables. Am J Vet Res 1998;59:938–944

10. Torres BT, Punke JP, Fu YC, et al: Comparison of canine stifle kinematic data collected with three different targeting models. Vet Surg 2010;39:504–512

11. Lu TW, O'Connor JJ: A three-dimensional computer graphics-based animated model of the human locomotor system with anatomical joint constraints. J Biomech 1998;31:116–116

12. Veldpaus FE, Woltring HJ, Dortmans LJ: A least-squares algorithm for the equiform transformation from spatial marker co-ordinates. J Biomech 1988;21:45–54

13. Yokoo T, Knight BW, Sirovich L: An optimization approach to signal extraction from noisy multivariate data. Neuroimage 2001;14:1309–1326

14. Kadaba MP, Ramakrishnan HK, Wootten ME, et al: Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. J Orthop Res 1989;7:849–860

15. Allen K, DeCamp C, Braden T, et al: Kinematic gait analysis of the trot in healthy mixed breed dogs. Vet Comp Orthop Traumatol 1994;7:148–153

16. Clements DN, Owen MR, Carmichael S, et al: Kinematic analysis of the gait of 10 labrador retrievers during treadmill locomotion. Vet Rec 2005;156:478–481

17. Budsberg SC, Verstraete MC, Reynolds LR, et al: Three dimensional non-invasive kinematics of the canine stifle. Vet Surg 1999;28:387–388

18. DeCamp CE: Kinetic and kinematic gait analysis and the assessment of lameness in the dog. Vet Clin North Am Small Anim Pract 1997;27:825–840

Table 3.1. Marker Locations for Kinematic Modeling of a Canine Stifle Unilaterally

Femoral Markers
Greater trochanter
2 cm caudal to the greater trochanter
2 cm cranial to the greater trochanter
2 cm dorsal to the greater trochanter
2 cm ventral to the greater trochanter
Craniolateral aspect of the quadriceps m.
Lateral femoral condyle
Medial femoral condyle*
Tibial markers
Fibular head
Proximal aspect of tibial crest*
Distal aspect of tibial crest*
Junction of gastrocnemius m. and tendon
Medial malleolus*
Lateral malleolus
Gait determinant marker
Metatarsophalangeal joint #5

*Markers that are removed during the acquisition of dynamic trials.

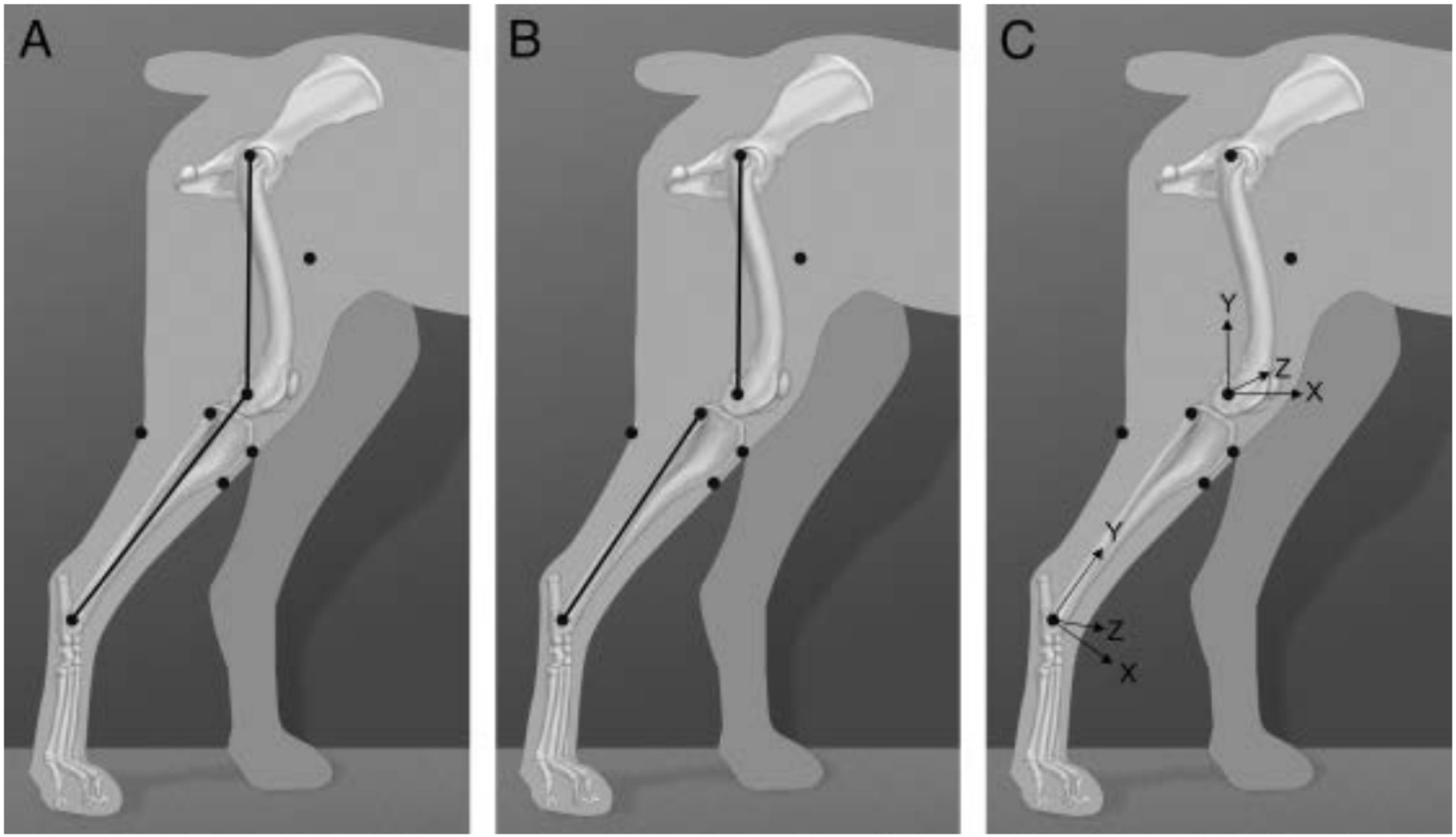


Figure 3.1. Illustrative representation of the body segments and kinematic marker placement on the skin of the canine hind limb. (A) Sagittal Linear Model (LIN), (B) Sagittal Segmental Model (SEG), (C) Joint Coordinate System Model (JCS).

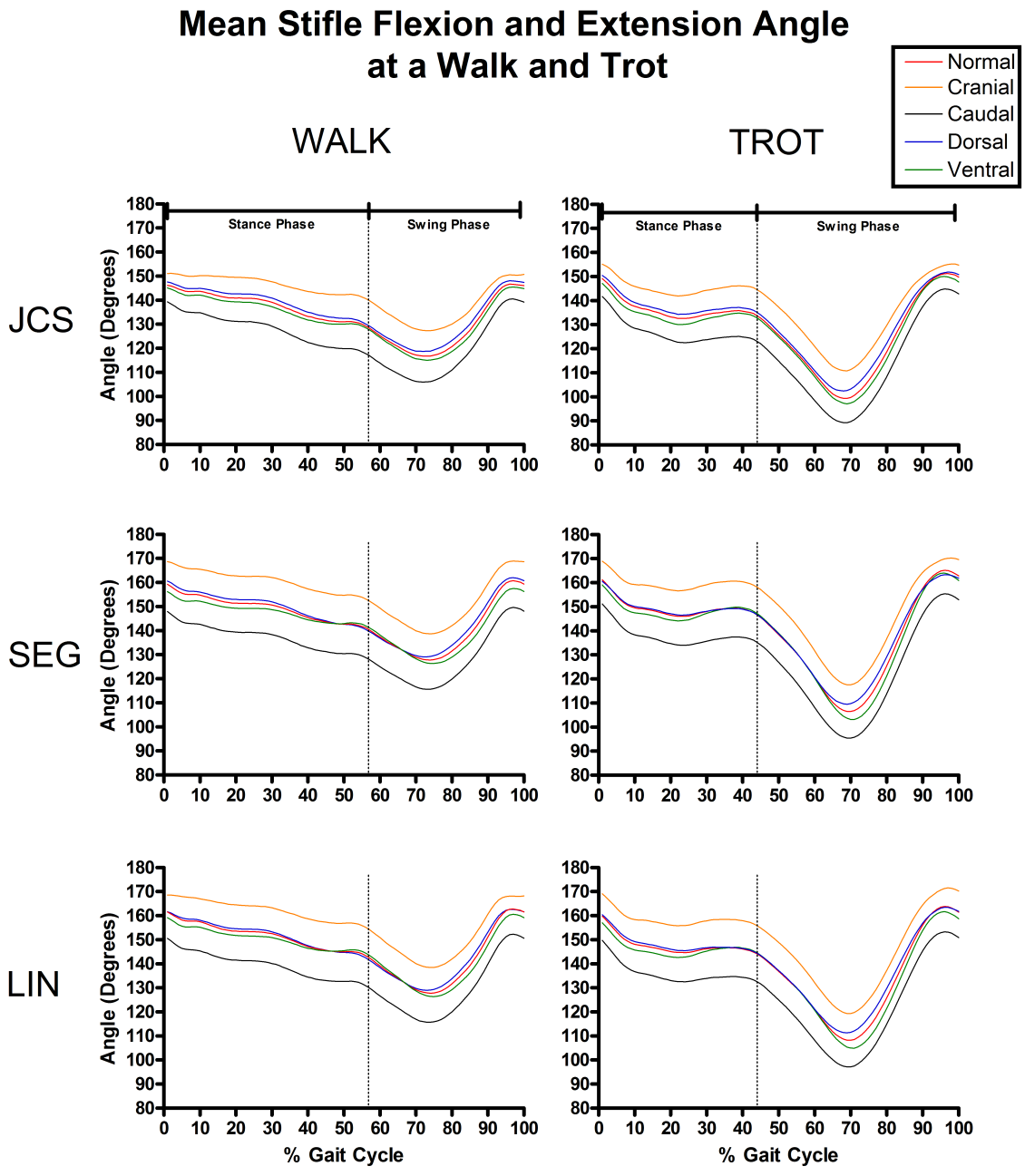
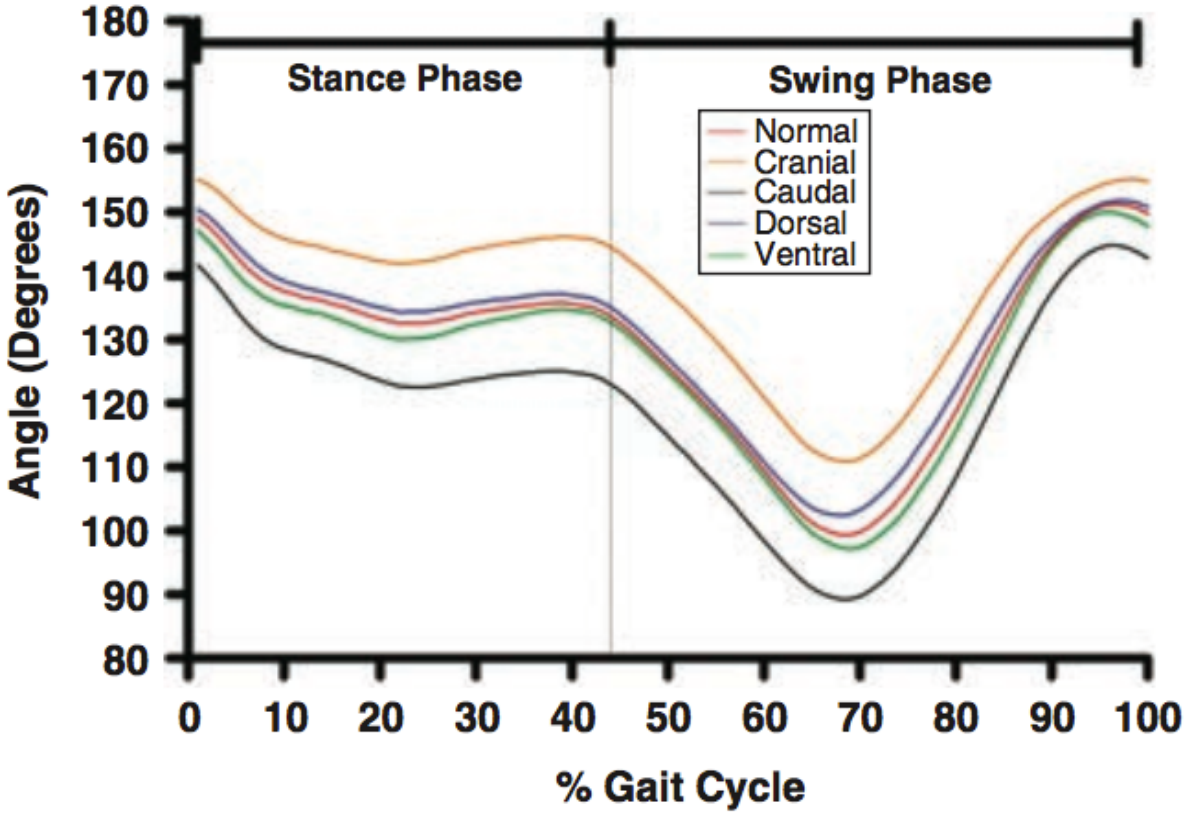
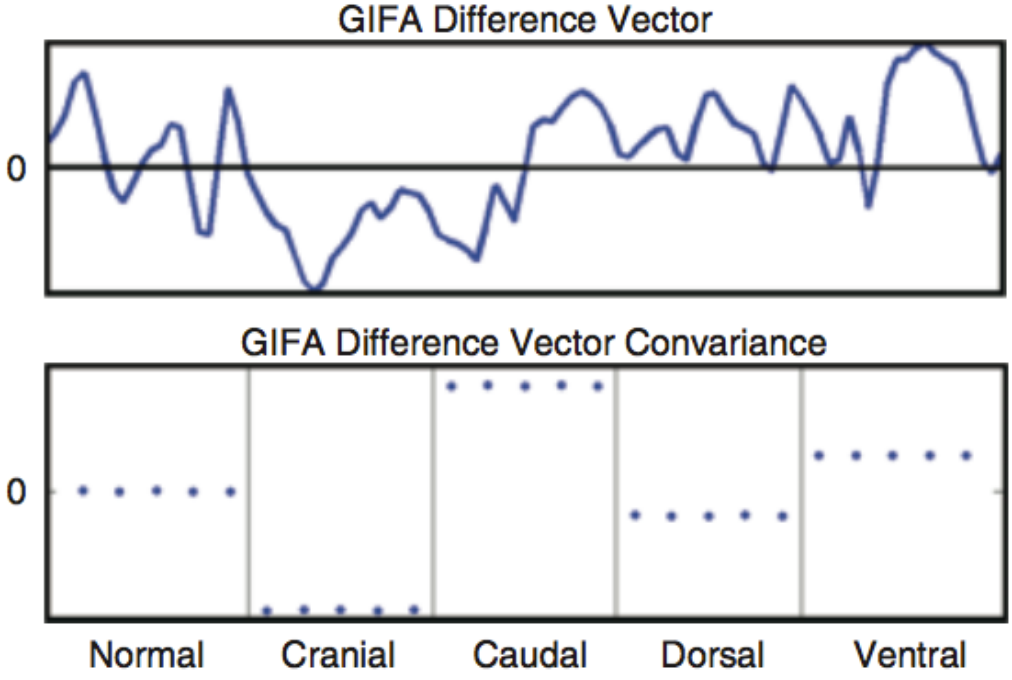


Figure 3.2. Graphs of mean stifle flexion and extension angles for all dogs at a walk and a trot with all 3 methods and greater trochanter (GT) locations illustrated. Quantitative angular change is indicated by the appropriate waveform.

Figure 3.3. Mean stifle flexion and extension angle with Joint Coordinate System Model (JCS) at a trot with 95% confidence intervals for an individual dog measured with differing greater trochanter (GT) locations. Significant differences, as illustrated by this comparison between GT locations, were found for all dogs within all methods at both a walk and trot. The temporal differences between GT locations are indicated by the Generalized Indicator Function Analysis (GIFA) Difference Vector plot. GIFA produces a multidimensional vector representing the most significant difference between the groups being compared. For illustrative purposes, this vector is depicted on the graph as a waveform corresponding to the temporal differences between gaits. Changes in amplitude away from baseline [0] correspond to the degree of difference detected between groups. However, the establishing vector is unitless and therefore the direction of waveform movement along the vertical axis, away from baseline [0], is arbitrary. The GIFA Difference Vector Covariance plot depicts a statistically significant change between GT locations. Each (•) represents an individual trial. Small movements along the vertical axes within a group indicate slight variation between individual trials within that group. Differences in vertical axes position between the groups (GT locations) indicate significant differences between them. The distance between the groups along the vertical axes denotes the degree of difference between them. The actual position of the groups along the vertical axis represents a relative quantity.


Stance Phase
Swing Phase
Normal
Cranial
Caudal
Dorsal
Ventral
Angle (Degrees)
180
170
160
150
140
130
120
110
100
90
80
0
10
20
30
40
50
60
70
80
90
100
% Gait Cycle


GIFA Difference Vector
0
GIFA Difference Vector Convariance
0
Normal
Cranial
Caudal
Dorsal
Ventral

CHAPTER 4

THE EFFECT OF EXAMINER VARIABILITY ON MULTIPLE CANINE STIFLE KINEMATIC GAIT COLLECTIONS IN A 3-DIMENSIONAL MODEL[1]

[1]Torres B.T., Gilbert P.J., Reynolds L.R., Fu Y.C., Navik J.A., Sornborger A., and Budsberg S.C. 2014. *Veterinary Surgery*. doi: 10.1111/j.1532-950X.2014.12311.x. Reprinted here with permission of publisher.

Abstract

Objective: To evaluate examiner variability in a superficial skin marker model of canine stifle kinematics.

Study Design: Experimental.

Animals: Six clinically normal dogs.

Methods: Dogs had 11 retroreflective markers fixed to the skin on the right hindlimb. Dogs were trotted 5 times through the calibrated testing space and this was repeated on 4 different testing days. Examiner A applied all markers to a dog and collected 6 good trials for analysis. The markers were then removed and Examiner B immediately repeated the process on the same dog. This was repeated for each dog on the 4 testing days. The dogs were trotted at a velocity of 1.70–2.10 m/s through the testing space to obtain the dynamic data sets. Comparisons were performed with Fourier analysis and Generalized Indicator Function Analysis (GIFA). Significance was set at $P < .05$ for all comparisons.

Results: Fourier analysis and GIFA found differences within and between examiners. Fourier analysis found no differences in sagittal and transverse planes for the experienced (A) and novice examiner (B), respectively. Fourier analysis detected fewer differences for the experienced examiner (A).

Conclusion: Variability occurs within and between examiners using the same kinematic model. Transverse and frontal plane kinematics produce variable results between examiners. Prior experience with the model reduces the amount of variability and results in consistent and repeatable sagittal plane kinematic data collection.

Introduction

Three-dimensional kinematic analysis is used for the study of normal and pathologic locomotion.[1,2] For this analytical tool to become widely accepted as useful and clinically relevant in veterinary medicine, its repeatability and sources of variability must be established. Previous research has identified sources of variability for kinetic data.[3] However, there are currently no reports establishing the repeatability and sources of variability during 3-dimensional kinematic testing.

The objectives of this study were to (1) assess the intra-examiner variability on 4 separate testing sessions, and (2) assess the inter-examiner variability on 4 separate testing sessions between an experienced examiner (A) and a novice examiner (B) using a 3-dimensional, superficial skin marking system.[4–7] The hypotheses tested was that intra- and inter-examiner differences would exist within and between testing days and that the level of examiner experience would not influence variability.

Materials And Methods

Animals

Six adult dogs (body weight 20–30 kg) from a research colony were evaluated in this study. Use of these animals was approved by the University of Georgia Institutional Animal Care and Use Committee (AUP # - A2006-10042-c1). All dogs had normal bilateral hip and stifle radiographs, force plate analysis, complete blood counts, serum biochemistry analysis, and physical examinations before the study. The dogs were housed indoors in a climate-controlled environment and fed commercial dog food ad libitum.

Motion Data Collection

A 3-dimensional model of the canine stifle was utilized in this study as previously described.[4–7] In this method, the segment of femur and tibia were assumed as a rigid body, and the local coordinate system for each segment was defined by markers attached on the segments during static calibration. Three nonorthogonal unit vectors of these axes described joint motion.[8] A toe marker was utilized to define the gait cycle as previously described.[4] Velocity and acceleration were recorded with a series of 5 photocells placed 0.5 m apart and 0.5 m above the walkway.[9]

Eleven spherical retroreflective markers (8 mm diameter) were fixed with double-sided tape and cyanoacrylate to the right hindlimb (Table 4.1). All dogs were short-haired and hair was not clipped before application. A 3-dimensional testing space was established on a 13-meter walkway. Right-handed orthogonal coordinate axes were used to describe the testing space in 3 dimensions with 0,0,0 (X, Y, Z) located in the center of the testing space. Eight infrared cameras (Vicon MX03, Vicon Motion Systems, Inc., Centennial, CO) arranged around the gait platform captured marker location data at 200Hz. Each day, before data collection, the system was calibrated with a calibration frame (Vicon Peak Motus L-Frame, Vicon- Peak, Centennial, CO) of known dimensions and by dynamic linearization with a custom made 0.700 m wand. Data were recorded and analyzed by a motion-analysis program (Peak Motus 9, Vicon Motion Systems, Inc.). The kinematic model was established as previously described4 on a computer software program (MATLAB, version 7.0 R14, The MathWorks Inc, Natick, MA).

Two different examiners were evaluated. Both examiners had knowledge of canine anatomy. Examiner A had prior experience with kinematic data collection using the current model. Examiner B had no prior experience. Examiner B was provided with a brief study

description, a list of marker locations (Table 4.1), as well as a written description of the markers and method of placement before the study began.

Data Collection. Examiner A applied all markers. Initially, a static trial of the dog being tested was collected. Then, 4 markers (noted * on Table 4.1) were removed during subsequent dynamic trials. These markers were reconstructed from the static trial and were employed as virtual markers during the dynamic trials. The test dog was then recorded moving through the calibrated testing space in a trot at an average velocity of 1.70–2.10 m/s and an average acceleration of -0.50–0.50 m/s^2. Six good trials were collected for analysis. Examiner A then removed the markers with acetone, leaving no visual trace. Examiner B then immediately applied the same markers, repeating the process. This was repeated for each dog on 4 separate testing days (Days 0, 3, 5, and 9). The order of marker application between examiner A and examiner B as well as the order of dog was randomized. The same handler gaited all dogs. Passes in which the dog visibly changed velocity, turned its head, broke stride, or made any aberrant motions were discarded immediately. In the case of any loss of markers requiring reattachment, data collection of all trials on that day was to be repeated.

Data Analysis

Waveforms were generated during each gait cycle and were compiled graphically, represented with 95% confidence intervals (Figure 4.1). These waveforms were compared by Fourier analysis[5,6] and Generalized Indicator Function Analysis (GIFA).[5–7,10] Eight Fourier coefficients were used to characterize stifle joint motion. All analyses were performed using SAS V 9.2 (SAS Institute, Cary, NC). A paired t-test was used to assess differences in Fourier

coefficients (A1–A8 and B1– B8) between examiners for each day and plane of motion. The t-tests were performed on the difference of the mean coefficient for each dog (averaged over 6 replications) for Examiner A and the mean coefficient for each dog for Examiner B (averaged over 6 replications) for each day, plane, and coefficient separately. All hypothesis tests were 2-sided and significance was set at $P<.05$ for each test. A repeated measures analysis was used to test for difference in Fourier coefficients (A1–A8 and B1–B8) between days for each examiner and plane. The repeated measures analysis was performed on the data averaged over 6 replications and a Tukey-adjusted P-value was used for multiple comparisons. The hypothesis test was 2-sided and significance was set at $P<.05$. The GIFA was used to compare waveforms as previously described,[5–7] with significance set at $P <.05$.

Results

Sagittal (flexion and extension), transverse (internal and external rotation), and frontal (abduction and adduction) plane kinematics during movement of the distal segment relative to the proximal segment for the stifle joint were generated and collected from each dog during each dynamic gait cycle at a trot. Each plane of motion was evaluated separately for comparative analysis.

Fourier Analysis

Intra-Examiner Results. Examiner A had intra-examiner differences in the frontal plane and in the transverse plane (Table 4.2) but no intra-examiner differences in the sagittal plane. Examiner B had intra-examiner differences in the frontal plane and in the sagittal plane (Table 4.3) but no intra- examiner differences in the transverse plane.

Inter-Examiner Results. There were significant differences between the Fourier coefficients produced by Examiners A and B in all planes of motion (Table 4.4).

GIFA

Sagittal waveform analysis with GIFA found significant intra- and inter-examiner differences within and between all testing days. These differences were similar for both the experienced (A) and novice (B) examiner.

Discussion

Both research hypotheses in this study were accepted, that is, intra- and inter-examiner differences existed within and between testing days, and the level of examiner experience did not influence variability. While both examiners produced similar sagittal waveforms (Figure 4.1), GIFA was able to detect significant differences within and between all testing days for all planes of motion, indicating that while temporal and examiner variability exists, experience level does not affect variability. Fourier analysis also found significant differences within 2 planes of motion and between all planes of motion although the extent of differences was less than with GIFA.

Sagittal plane kinematics provided consistent results for the experienced examiner (A) with no differences detected by Fourier analysis. Historically, hindlimb motion in the sagittal plane has been the focus of motion analysis in veterinary medicine.[1,11–13] This is likely because of the available camera equipment (2-dimensional systems) and a quantitatively large degree of motion in the sagittal plane compared to the transverse and frontal planes. However, failure to address simultaneous motion occurring in the transverse and frontal planes limits the

understanding of true 3-dimensional joint motion and hinders our ability to advance in the field of veterinary kinematics. Hence, the intent was to examine all planes of motion in the current study.

In this study, both transverse and frontal plane kinematics produced variable data for the experienced examiner (A). Interestingly, the transverse plane produced consistent data for the novice examiner (B). The reason for the difference between examiners is unknown. The evaluation of the additional planes of motion (transverse and frontal) can prove challenging. Marker visualization by the cameras (most notably medially placed markers) can be problematic in both people and animals. Marker visualization can be difficult during data collection of dogs because of truncal and/or handler concealment of markers.[6] In the current study, this issue was addressed by the implementation of virtual markers, as previously described.[4–7] Additionally, the amount of stifle motion that occurs in these planes of motion is small compared to the quantitatively larger sagittal plane (Figure 4.1). The minimal motion in these planes increases the complexity of accurate data acquisition and analysis by magnifying the sources of variability. While overall, the differences in these planes were small, further research is warranted to improve data acquisition in these planes of motion.

Both 2-dimensional and 3-dimensional systems have been used for veterinary kinematic gait analysis.[1,4,5,7,11–19] Lower cost, 2-dimensional systems can obtain accurate and repeatable sagittal plane data.[15,17] However, 2-dimensional systems suffer from parallax and perspective error, and simultaneous collection of transverse and frontal planes of motion is not possible.[17,20] Parallax error occurs as the subject moves away from the optical axis of the camera and can be minimized but not eliminated.[20] Perspective error occurs when the subject moves out of the calibrated plane of motion (sagittal, transverse, or frontal plane). Methods of estimating and

correcting for parallax and perspective error have been evaluated,[20,21] but clinical application is often difficult.[20] It is possible that use of a treadmill may minimize these sources of error by providing a stationary platform for ambulation. However, while sagittal plane kinematic of the canine hindlimb during overground and treadmill-based walking and trotting are comparable, small differences in the transverse and frontal planes have been described.[5] Three-dimensional systems do not suffer from parallax or perspective error and allow simultaneous collection of all planes of joint motion. The model used in the current study is a unique superficial skin marker system of the canine hindlimb that establishes a rigid body model of the canine stifle that can be used to report true 3-dimensional joint motion.

The choice of analysis methodology in veterinary gait studies is an important consideration. Fourier analysis is common in veterinary kinematic studies.[1,11–13,18] Some reports have limited the analysis of joint motion to essential coefficients, defined as the coefficients needed to reconstruct ≥95% of the waveform. These investigations found the first 3 coefficients were essential and used them to evaluate stifle joint motion in dogs at a trot.[11,12,18] Interestingly, our previous study detected significant differences in an extended range of coefficients (≥8 Fourier coefficients) from dogs at a trot.[5,6] The current study yielded similar findings. Recently, GIFA was introduced as a method of comparing gait waveforms in dogs.[5–7,22] Previous studies have shown GIFA detected differences between visually similar gait waveforms when Fourier analysis did not.[5,6,22] Multiple studies, including this one, use GIFA and Fourier analysis concurrently to assess dog gaits.[5,6,22] In the current study, approximately 35% of the intra-examiner differences and 50% of the inter-examiner differences were detected in coefficients beyond the previously established essential coefficients for the stifle joint, which raises the question of how many coefficients should be evaluated. The additional, non-essential coefficient

data may provide valuable comparative and clinically important information but current work is not conclusive.

Experience level did not affect the ability of the examiner to detect differences although Fourier analysis found fewer differences in the experienced examiner. Minor inconsistencies in marker location can cause variations resulting in a shift in the vertical position of the gait waveform. Recognition of this variation has led to the recommendation for data normalization.[1,12] Others have found that differences are more likely due to changes in the gait patterns of subjects and less likely related to inconsistencies in marker location.[23,24] A recent study demonstrated that normalization reduces but does not eliminate differences between individual dogs and the evaluation of pooled data is unaffected.[7] Interestingly, GIFA is unaffected by the position of waveforms along the vertical axis and thus the differences detected by this analysis are likely because of true differences in the waveform shapes and not just inconsistencies in marker placement. However, it is possible that the differences for both analysis methods are because of the cumulative effect of small differences created on each testing day.

The goal of objective kinematic modeling is to provide researchers and clinicians with a biologically accurate and clinically relevant means of evaluating musculoskeletal motion during ambulation. How the data obtained from these models is analyzed is also critical. Evaluation methods must assess the entire gait cycle or gait waveform rather than a single point, data analysis. Inherent differences in analysis methods may enhance or diminish the ability to detect differences. Currently, there is not a single ideal method of kinematic data analysis. Instead, the synergistic use of multiple analyses may provide a composite assessment of gait kinematics. For example, while Fourier analysis can be used to determine if 2 gait cycles are similar, it is unable

to determine where along the gait cycle they differ. The addition of GIFA allows determination of where along the gait cycle these differences occur.[6] This added ability to assess where in the stance or swing phases difference occur may be beneficial.

Skin movement artifact with the use of skin marker systems has been a longstanding concern for gait analysis in people and animals. A common strategy is to place markers over bony landmarks. This has the advantage of providing an easily identified and repeatable location for marker placement. In addition, these marker locations have minimal underlying soft tissue that may reduce skin and soft tissue movement artifact. Kim et al.[25] recently evaluated skin movement artifact in a superficial skin marker model of the canine hindlimb. They found that skin movement affected gait data and that these changes occurred in a cyclic pattern throughout the gait cycle. Recommendations were made to characterize skin movement in canine kinematics to improve skin marker systems and more accurately represent underlying bone movement.[25] However, skin movement must be evaluated at all sites of marker attachment in the model being used. Until additional data are available regarding skin marker movement at all marker sites, it must be accepted that kinematic data includes some skin movement artifact that is unrelated to movement of the underlying bones.[1] In the present study, skin movement was addressed by use of an unweighted least squares method.[4,26] It has been suggested that advanced algorithms, such as an optimization method, may also help minimize skin movement artifact.[4,27]

Efforts were made to reduce sources of experimental error. The order of marker application between examiners as well as the order of dog was randomized. The same handler gaited all dogs. The first examiner was not allowed to observe the application or removal of markers by the second examiner. Efforts were made to remove all signs of previous marker

attachment on the dogs before application of markers by the second examiner. No markers became detached during data collection.

Intra- and inter-examiner differences were found for both the experienced and novice examiner. While each examiner produced similar waveforms, the extent of differences detected varied according to the analysis method. The GIFA was unaltered by experience level while Fourier analysis found that experience reduced variability, reflecting differences inherent to the analysis methods. These findings indicate that consistent and repeatable kinematic data from the sagittal plane can be obtained from the kinematic model tested but experience, and intra- and inter-examiner variability can occur. Despite the use of a 3-dimensional system, data acquisition in the frontal and transverse planes remains inconsistent and refinement of the technique is necessary to improve reliability and accuracy in these planes.

References

1. DeCamp CE, Soutas-Little RW, Hauptman J, et al: Kinematic gait analysis of the trot in healthy greyhounds. Am J Vet Res 1993;54:627–634

2. Bockstahler BA, Henninger W, Muller M, et al: Influence of borderline hip dysplasia on joint kinematics of clinically sound Belgian Shepherd dogs. Am J Vet Res 2007;68:271– 276

3. Rumph PF, Steiss JE, West MS: Interday variation in vertical ground reaction force in clinically normal Greyhounds at the trot. Am J Vet Res 1999;60:679–683

4. Fu YC, Torres BT, Budsberg SC: Evaluation of a three-dimensional kinematic model for canine gait analysis. Am J Vet Res 2010;71:1118–1122

5. Torres BT, Moens NM, Al-Nadaf S, et al: Comparison of overground and treadmill-based gaits of dogs. Am J Vet Res 2013;74:535–541

6. Torres BT, Punke JP, Fu YC, et al: Comparison of canine stifle kinematic data collected with three different targeting models. Vet Surg 2010;39:504–512

7. Torres BT, Whitlock D, Reynolds LR, et al: The effect of marker location variability on noninvasive canine stifle kinematics. Vet Surg 2011;40:715–719

8. Grood ES, Suntay WJ: A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J Biomech Eng 1983;05:136–144

9. Punke JP, Speas AL, Reynolds LR, et al: Kinetic gait and subjective analysis of the effects of a tachykinin receptor antagonist in dogs with sodium urate-induced synovitis. Am J Vet Res 2007;68:704–708

10. Yokoo T, Knight BW, Sirovich L: An optimization approach to signal extraction from noisy multivariate data. Neuroimage 2001;14:1309–1326

11. Bennett RL, DeCamp CE, Flo GL, et al: Kinematic gait analysis in dogs with hip dysplasia. Am J Vet Res 1996;57:966– 971

12. DeCamp CE, Riggs CM, Olivier NB, et al: Kinematic evaluation of gait in dogs with cranial cruciate ligament rupture. Am J Vet Res 1996;57:120–126

13. Hottinger HA, DeCamp CE, Olivier NB, et al: Noninvasive kinematic analysis of the walk in healthy large-breed dogs. Am J Vet Res 1996;57:381–388

14. Clements DN, Owen MR, Carmichael S, et al: Kinematic analysis of the gait of 10 labrador retrievers during treadmill locomotion. Vet Rec 2005;156:478–481

15. Feeney LC, Lin CF, Marcellin-Little DJ, et al: Validation of two- dimensional kinematic analysis of walk and sit-to-stand motions in dogs. Am J Vet Res 2007;68:277–282

16. Gillette RL, Zebas CJ: A two-dimensional analysis of limb symmetry in the trot of Labrador retrievers. J Am Anim Hosp Assoc 1999;35:515–520

17. Kim J, Rietdyk S, Breur GJ: Comparison of two-dimensional and three-dimensional systems for kinematic analysis of the sagittal motion of canine hind limbs during walking. Am J Vet Res 2008;69:1116–1122

18. Schaefer SL, DeCamp CE, Hauptman JG, et al: Kinematic gait analysis of hind limb symmetry in dogs at the trot. Am J Vet Res 1998;59:680–685

19. Torres BT, Punke JP, Fu YC, et al: Comparison of canine stifle kinematic data collected with three different targeting models. Vet Surg 2010; 39 504–512

20. Kirtley C: Measurement of gait kinematics, in Clinical gait analysis: theory and practice. St Louis, MO: Churchill Livingston Elsevier, 2006, p 39–51

21. Li JA, Bryant JT, Stevenson JM: Single camera photogrammetric technique for restricted 3D motion analysis. J Biomed Eng 1990;12:69–74

22. Al-Nadaf S, Torres BT, Budsberg SC: Comparison of two methods for analyzing kinetic gait data in dogs. Am J Vet Res 2012;73:189–193

23. Gorton GE, 3rd, Hebert DA, Gannotti ME: Assessment of the kinematic variability among 12 motion analysis laboratories. Gait Posture 2009;29:398–402

24. Kadaba MP, Ramakrishnan HK, Wootten ME, et al: Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. J Orthop Res 1989;7:849–860

25. Kim SY, Kim JY, Hayashi K, et al: Skin movement during the kinematic analysis of the canine pelvic limb. Vet Comp Orthop Traumatol 2011;24:326–332

26. Veldpaus FE, Woltring HJ, Dortmans LJ: A least-squares algorithm for the equiform transformation from spatial marker coordinates. J Biomech 1988;21:45–54

27. Lu TW, O'Connor JJ: Bone position estimation from skin marker coordinates using global optimisation with joint constraints. J Biomech 1999;32:129–134

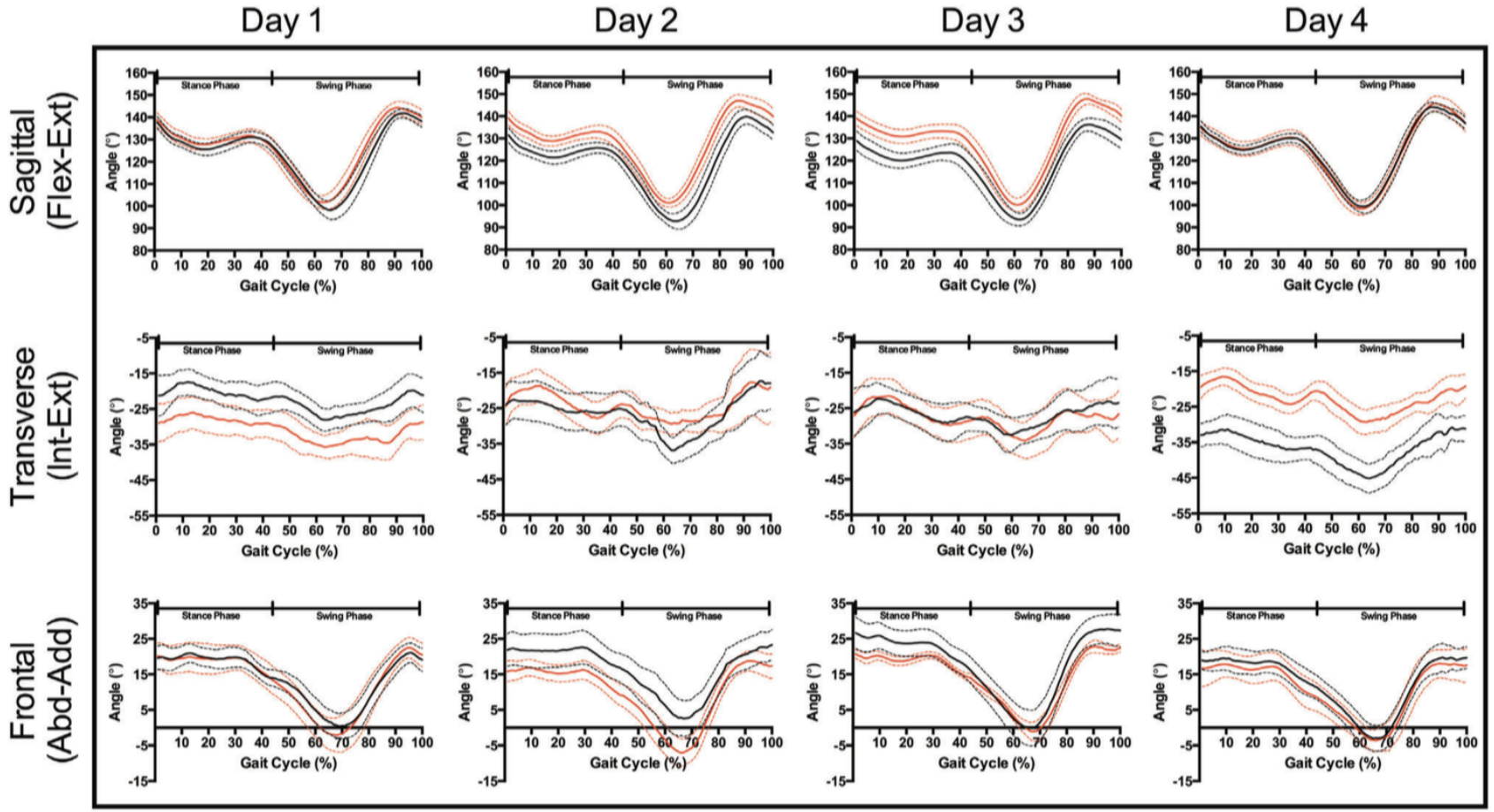


Figure 4.1. Mean (solid lines) stifle angles with 95% confidence intervals (dashed lines) obtained during testing days 1–4 from 6 dogs in a study of sagittal (flexion-extension [Flex-Ext]), transverse (internal-external rotation [Int-Ext]), and frontal (abduction–adduction [Abd–Add]) plane kinematics during a trot. Quantitative angular change during movement of the distal segment relative to the proximal segment was collected by an experienced examiner (A, red line) and a novice examiner (B, black line).

Table 4.1. Anatomic Landmarks for Skin Marker Locations for Kinematic Modeling of a Canine Hindlimb

Femur
Greater trochanter
Craniolateral aspect of the quadriceps m.
Lateral femoral condyle
Medial femoral condyle[a]
Tibia
Fibular head
Proximal aspect of tibial crest[a]
Distal aspect of tibial crest[a]
Junction of gastrocnemius m. and tendon
Medial malleolus[a]
Lateral malleolus
Phalange
Lateral metatarsophalangeal joint

[a]Markers removed during the acquisition of dynamic trials.

Table 4.2. Results (Tukey-Adjusted P-Value) of Intra-Examiner Fourier Analysis for Examiner A (Experienced)

Joint Motion	Day Comparison	A1	A2	A3	A4	A5	A6	A7	A8	B1	B2	B3	B4	B5	B6	B7	B8
Sagittal	1 vs 2	0.720	0.087	1.000	0.503	0.995	0.587	0.161	0.650	0.062	0.860	0.200	0.911	0.966	0.667	0.644	0.567
(Flexion-Extension)	1 vs 3	0.481	0.068	0.371	0.385	0.954	0.926	0.180	0.821	0.245	0.805	0.055	1.000	0.755	0.415	0.590	0.986
	1 vs 4	0.531	0.120	0.893	0.785	0.381	0.908	0.427	0.893	0.055	0.571	0.852	0.939	0.984	0.978	0.982	0.331
	2 vs 3	0.976	0.999	0.341	0.996	0.992	0.908	1.000	0.989	0.854	0.999	0.819	0.936	0.951	0.971	1.000	0.380
	2 vs 4	0.988	0.998	0.916	0.127	0.274	0.250	0.909	0.964	1.000	0.952	0.582	1.000	0.845	0.437	0.430	0.970
	3 vs 4	1.000	0.988	0.125	0.087	0.177	0.587	0.932	0.998	0.819	0.976	0.178	0.959	0.549	0.237	0.383	0.199
Transverse	1 vs 2*	0.566	0.433	0.250	**0.032**	0.874	0.644	0.373	0.996	0.359	0.996	0.880	0.475	0.793	0.819	0.987	0.997
(Internal-External	1 vs 3*	0.875	0.980	**0.027**	0.853	1.000	0.646	0.977	0.784	0.556	0.998	0.872	0.328	0.910	0.764	0.967	0.990
rotation)	1 vs 4	0.823	0.504	0.526	0.990	0.998	0.981	0.907	0.961	0.908	0.992	0.943	0.997	0.484	0.989	0.974	0.976
	2 vs 3*	0.940	0.256	0.603	**0.007**	0.917	0.126	0.206	0.886	0.983	0.976	0.463	**0.025**	0.994	1.000	0.999	0.959
	2 vs 4	0.968	0.999	0.941	0.056	0.787	0.850	0.752	0.993	0.734	1.000	0.578	0.372	0.949	0.944	0.872	0.930
	3 vs 4	1.000	0.308	0.303	0.694	0.991	0.428	0.710	0.968	0.907	0.965	0.997	0.426	0.854	0.911	0.813	1.000
Frontal	1 vs 2	0.800	0.535	0.290	0.366	0.811	0.969	0.989	0.998	0.434	0.903	0.301	0.063	0.857	0.923	0.992	0.181
(Abduction-Adduction)	1 vs 3*	1.000	0.818	0.580	0.395	0.300	0.988	0.104	0.871	0.181	0.981	0.988	**0.045**	0.772	0.997	0.583	**0.023**
	1 vs 4*	0.859	0.206	0.522	0.171	0.233	0.825	0.858	0.977	0.124	0.966	0.506	**0.043**	0.354	0.682	0.366	0.986
	2 vs 3	0.851	0.959	0.944	1.000	0.786	0.999	0.176	0.937	0.930	0.990	0.461	0.998	0.998	0.844	0.421	0.674
	2 vs 4	0.999	0.894	0.967	0.956	0.691	0.976	0.963	0.934	0.840	0.670	0.977	0.997	0.797	0.958	0.243	0.305
	3 vs 4*	0.903	0.636	1.000	0.941	0.998	0.948	0.361	0.656	0.996	0.836	0.696	1.000	0.878	0.565	0.978	**0.044**

A1–A8, cosine coefficients; B1–B8, sine coefficients.

*Significant difference noted between days—the bold *P*-values indicate which Fourier coefficient was significantly different within examiner for the days being compared.

Table 4.3. Results (Tukey-Adjusted P-Value) of Intra-Examiner Fourier Analysis for Examiner B (Novice)

Joint Motion	Day Comparison	A1	A2	A3	A4	A5	A6	A7	A8	B1	B2	B3	B4	B5	B6	B7	B8
Sagittal	1 vs 2*	**0.011**	0.233	0.734	0.994	0.741	0.972	0.886	0.667	0.675	0.940	0.661	0.804	0.458	0.765	1.000	0.580
(Flexion-Extension)	1 vs 3*	0.114	**0.025**	0.988	0.230	0.376	0.798	0.244	0.483	0.119	0.999	**0.024**	0.852	0.936	0.887	0.982	0.956
	1 vs 4*	**0.041**	**0.029**	0.936	0.285	0.441	0.253	0.120	0.704	**0.013**	**0.002**	0.583	1.000	0.642	0.996	0.943	0.964
	2 vs 3	0.625	0.605	0.548	0.153	0.916	0.962	0.611	0.083	0.594	0.884	0.191	1.000	0.792	0.994	0.980	0.858
	2 vs 4*	0.912	0.650	0.402	0.193	0.953	0.456	0.368	0.159	**0.001**	**0.001**	0.111	0.807	0.989	0.636	0.940	0.325
	3 vs 4*	0.942	1.000	0.993	0.999	0.999	0.737	0.971	0.981	**0.000**	**0.003**	**0.002**	0.856	0.928	0.781	0.998	0.762
Transverse	1 vs 2	0.627	0.514	0.998	0.996	0.866	0.950	0.650	0.989	0.976	0.322	0.785	0.939	0.915	0.993	0.457	0.994
(Internal-External	1 vs 3	0.930	0.747	0.998	0.995	0.389	0.997	0.933	0.273	0.474	0.998	0.947	0.970	0.993	0.903	0.999	1.000
rotation)	1 vs 4	0.562	0.976	0.973	0.999	0.630	0.998	0.913	0.658	1.000	0.627	0.918	1.000	0.981	0.999	0.999	0.900
	2 vs 3	0.926	0.117	1.000	0.966	0.823	0.877	0.325	0.166	0.714	0.406	0.473	0.999	0.798	0.780	0.533	0.998
	2 vs 4	1.000	0.305	0.995	0.981	0.971	0.985	0.952	0.473	0.971	0.942	0.421	0.924	0.737	0.999	0.539	0.972
	3 vs 4	0.886	0.931	0.994	1.000	0.973	0.977	0.609	0.885	0.459	0.727	1.000	0.960	1.000	0.843	1.000	0.927
Frontal	1 vs 2*	0.989	0.598	1.000	0.369	**0.013**	0.982	0.310	0.421	0.547	0.958	0.506	0.828	0.963	0.990	0.379	0.969
(Abduction-Adduction)	1 vs 3*	0.101	0.283	0.626	0.636	**0.015**	0.418	0.908	0.848	0.413	0.284	0.124	0.519	0.776	0.996	0.465	0.757
	1 vs 4	0.589	0.243	0.431	0.624	0.201	0.764	0.594	0.730	0.552	0.732	0.167	0.360	0.789	0.735	0.799	0.648
	2 vs 3	0.171	0.930	0.584	0.963	1.000	0.629	0.674	0.123	0.995	0.540	0.774	0.947	0.963	1.000	0.998	0.947
	2 vs 4	0.768	0.894	0.394	0.967	0.469	0.928	0.950	0.082	1.000	0.949	0.862	0.835	0.968	0.884	0.877	0.882
	3 vs 4	0.625	1.000	0.986	1.000	0.504	0.929	0.929	0.996	0.994	0.840	0.998	0.991	1.000	0.847	0.936	0.998

A1–A8, cosine coefficients; B1–B8, sine coefficients.

*Significant difference noted between days—the bold *P*-values indicate which Fourier coefficient was significantly different within examiner for the days being compared.

Table 4.4. Results (P-Value) of Inter-Examiner Fourier Analysis Between Examiners A (Experienced) and B (Novice)

Joint Motion	DAY	A1	A2	A3	A4	A5	A6	A7	A8	B1	B2	B3	B4	B5	B6	B7	B8
Sagittal	Day 1	0.111	0.198	0.762	0.488	0.189	0.119	0.462	0.770	0.073	0.910	0.229	0.887	0.336	0.716	0.712	0.725
(Flexion-Extension)	Day 2*	0.622	0.207	0.226	**0.046**	0.529	**0.005**	**0.037**	**0.030**	**0.045**	0.250	0.110	0.784	0.999	0.423	0.270	0.762
	Day 3*	**0.006**	0.484	0.459	0.420	0.231	0.561	0.501	0.986	0.658	0.126	0.158	0.471	0.124	0.092	0.305	0.535
	Day 4*	0.421	0.843	0.556	0.115	0.124	**0.049**	0.370	0.891	**0.004**	**0.042**	**0.007**	0.708	0.738	0.819	0.340	0.139
Transverse	Day 1*	0.827	0.621	0.284	0.543	**0.032**	0.532	0.834	0.216	0.793	0.918	0.701	0.484	0.635	0.618	0.375	0.378
(Internal-External	Day 2*	0.655	0.634	0.799	0.193	0.973	**0.038**	1.000	0.153	0.666	0.070	0.881	0.562	0.347	0.851	0.086	0.828
rotation)	Day 3	0.859	0.787	0.114	0.079	0.995	0.395	0.414	0.786	0.229	0.460	0.296	0.162	0.998	0.158	0.525	0.369
	Day 4	0.518	0.076	0.588	0.386	0.440	0.369	0.860	0.821	0.757	0.532	0.388	0.789	0.301	0.906	0.933	0.175
Frontal	Day 1	0.474	0.748	0.768	0.965	0.590	0.356	0.695	0.797	0.714	0.373	0.839	0.075	0.598	0.245	0.819	0.879
(Abduction-Adduction)	Day 2	0.170	0.669	0.147	0.489	0.196	0.545	0.140	0.078	0.833	0.264	0.586	0.421	0.854	0.940	0.231	0.194
	Day 3*	**0.026**	0.301	0.903	0.711	0.238	0.507	0.052	0.890	0.476	0.560	**0.036**	0.453	0.939	0.209	0.609	0.189
	Day 4	0.810	0.496	0.609	0.959	0.687	0.556	0.464	0.129	0.311	0.584	0.647	0.276	0.220	0.372	0.330	0.130

A1–A8, cosine coefficients; B1–B8, sine coefficients.

*Significant difference on a given day—the bold *P*-values indicate which Fourier coefficient was significantly different between examiners for the given day.

CHAPTER 5

COMPARISON OF OVERGROUND AND TREADMILL-BASED GAITS OF DOGS[1]

[1]Torres B.T., Moëns N.M., Al-Nadaf S., Reynolds L.R., Fu Y.C., and Budsberg S.C. 2013. *American journal of veterinary research.* 74.4: 535-541. Reprinted here with permission of publisher.

Abstract

Objective: To compare overground and treadmill-based gaits of dogs.

Animals: 5 clinically normal adult mixed-breed dogs.

Procedures: To obtain dynamic gait data, 30 retroreflective markers were affixed bilaterally to specific regions of the hind limbs and pelvis of each dog. For each dog, 3-D joint motion data (sagittal [flexion and extension], transverse [internal and external rotation], and frontal [abduction and adduction] planes of motion) for the hip, femorotibial, and tarsal joints were acquired during walking and trotting through a calibrated testing space overground or on a treadmill. Comparison of data was performed via generalized indicator function analysis and Fourier analysis.

Results: Both overground and treadmill-based gaits produced similar waveforms in all planes of motion. Fourier analysis revealed no difference between overground and treadmill-based gaits in the sagittal plane of motion; however, small differences were detected between overground and treadmill-based gaits in the other 2 planes of motion. Additionally, femorotibial joint motion during walking did not differ among planes of motion. Generalized indicator function analysis was able to detect differences between overground and treadmill-based gait waveforms in all planes of motion for all joints during walking and trotting.

Conclusions and Clinical Relevance: In dogs, overground and treadmill-based gaits produced similar waveform shapes. Of the 3 planes of motion evaluated, only sagittal plane kinematic gait data were unaffected by mode of ambulation as determined via Fourier analysis. Sagittal kinematic gait data collected from dogs during overground or treadmill-based ambulation were comparable. However, analysis methods may affect data comparisons.

Introduction

The process of kinetic, or force platform, data collection in dogs is well established.[1–5] Kinematic data for dogs have been collected over many years, but the methods of collecting dynamic gait data and the subsequent analyses have varied. Both kinetic and kinematic gait evaluations have been performed with data collected during either overground[1–5] or treadmill-based[6–10] ambulation.

The use of treadmills provides the ability to collect a large quantity of data rapidly with the use of minimal laboratory space. However, debate continues regarding the use of treadmills for the collection of gait data. Recently, a study[7] compared kinetic gait data for lame and non-lame dogs obtained from a treadmill with embedded force plates against data obtained with standard force plates and found that both methods provided similar peak vertical force results for the forelimbs and hind limbs of lame and non-lame dogs during trotting. In that study,[7] it was noted that although vertical force measurements were obtained and compared, the treadmill force plates did not allow evaluation of medial-lateral and cranial-caudal forces. Additionally, frequent overlap of the fore- and hind paw strikes occurred. To the authors' knowledge, there are currently no reports of studies that have compared kinematic data from dogs during overground and treadmill-based dynamic gaits. In the study reported here, the hypothesis tested was that dynamic gait data collected from dogs during overground ambulation versus treadmill-based ambulation would differ.

Materials And Methods

Animals—Five adult mixed-breed dogs (weight range, 20 to 30 kg) from an established research colony were evaluated in this study. All dogs had no physical or radiographically detectable

pathological changes in the hip or stifle joints. For each dog, results of an initial force plate analysis, CBC, serum biochemical analysis and complete physical examination performed prior to initiation of the study indicated no abnormalities. The dogs were housed indoors in a climate-controlled environment and fed commercially available dog food ad libitum. Use of these animals was approved by the University of Georgia Institutional Animal Care and Use Committee.

The number of dogs in the study group was determined on the basis of a power analysis to detect a 5% difference with an α error of 0.05 and a β error of 0.8 for the first 3 Fourier coefficients for the hip joint, the first 5 coefficients for the femorotibial joint, and the first 6 coefficients for the tarsal joint.[11] On the basis of a previous study11 that used Fourier analysis, population size estimates for the hip and femorotibial joints were 5, whereas 16 animals were estimated to be needed for the tarsal joint.

Motion data collection—Thirty spherical retro-reflective markers (diameter, approx. 8 mm) were affixed with double-sided tape and cyanoacrylate to the right and left hind limbs and right and left sides of the pelvis (Table 5.1). A bilateral rigid-body segmental model of the canine hind limb and pelvis was used to collect kinematic data as described elsewhere.[12]

A 3-D testing space was established on a 13-m walkway. Right-handed orthogonal coordinate axes were used to describe the testing space in 3-D, with 0,0,0 (X,Y,Z) located in the center of the testing space. Prior to data collection on each testing day, the system was calibrated with a calibration frame[a] of known dimensions and by dynamic linearization with a custom-made 0.700-m wand. Marker locations were captured by a kinematic system of 8 infrared

cameras[b] arranged around the gait platform. Cameras captured sample data at 200 Hz. Data were recorded and analyzed by a motion analysis program.[c]

Initially, a static data collection was performed for each dog. Four markers on both the right and left hind limbs were removed during subsequent dynamic data collections (Table 5.1). These markers were mathematically reconstructed from the initial static data and were used as virtual markers during the dynamic data collections.[12–17] This use of virtual markers was necessitated by limitations in marker visibility during walking or trotting as a result of the partial or complete truncal concealment of certain markers. All data for individual dogs were obtained during 1 testing period on 1 day.

Overground gait data were recorded as each dog moved through the calibrated space at a walk and trot. The order in which each gait was performed was identical for all dogs. Each dog was walked across the testing space at a speed of 0.9 to 1.2 m/s and trotted across the testing space at a speed of 1.7 to 2.1 m/s. Each gait was recorded 5 times for analysis. Passes in which the dog visibly changed velocity, turned its head, broke stride, or made any aberrant motions were discarded immediately.

Treadmill gait data were recorded with dogs moving on the treadmill at a walk and trot. All dogs underwent treadmill training every other day for approximately 2 weeks prior to study initiation. The order in which each gait was performed was identical for all dogs. Individual dogs were introduced gently onto the treadmill.

Each dog was restrained with a standard harness that was loosely attached to the treadmill with a leash. The treadmill motion was initiated, and the speed was increased until a steady walk was achieved. A recording of the dog walking at a treadmill belt speed of 1.0 m/s was obtained. After approximately 10 seconds of steady ambulation at the defined speed, walking gait data

were recorded over an interval of 20 seconds. The treadmill speed was then slowly increased until a steady trot was achieved. A recording of the dog trotting at a treadmill belt speed of 1.9 m/s was obtained. After approximately 10 seconds of steady ambulation at the defined speed, trotting gait data were recorded over an interval of 20 seconds. The first 5 complete gait cycles were used for analysis. The harness used for securing the dogs to the treadmill was in place on all dogs during each period of overground or treadmill testing.

Although data were collected for both sides of the body, data from 1 body side were used for comparisons. This was necessitated by considerable marker concealment and data loss for the side of the dog on which the handler was located during overground testing. This problem was not present during treadmill testing. Comparisons of data collected during overground and treadmill testing were performed with data obtained from the same limb (right or left) for each individual dog. All data (overground and treadmill) for each dog were collected on the same day.

Data analysis—Waveforms were generated during each gait cycle for the overground and treadmill testing. The waveforms were compiled graphically with 95% confidence intervals. These waveforms were then compared via GIFA[15,18] and Fourier analysis.[11,15,19] Significance was set at a value of $P < 0.05$.

Eight Fourier coefficients were used to characterize hip, stifle, and tarsal joint motions. Comparison of the overground and treadmill Fourier coefficients was accomplished with a paired t test. All hypothesis tests were 2-sided, and the significance level was $\alpha = 0.05$. The paired t tests were performed with statistical analysis software.[d]

Results

Sagittal (flexion and extension), transverse (internal and external rotation), and frontal (abduction and adduction) plane kinematics during movement of the distal segment relative to the proximal segment for each of the 3 joints (hip, femorotibial, and tarsal joints) were generated and collected from each dog during each dynamic gait cycle for overground and treadmill-based gaits at both a walk and a trot. Each plane of motion was evaluated independently for comparative analysis (Figure 5.1).

Fourier analysis—No significant differences were found between overground and treadmill-based gaits during flexion and extension joint motion for each joint (hip, femorotibial, or tarsal joint) at both a walk and a trot (Table 5.2). Power calculations for the tarsal joint coefficients ranged from 0.23 to 0.89.

Significant ($P < 0.05$) differences were found for internal and external joint motion between overground and treadmill-based gaits as follows: the hip, femorotibial, and tarsal joints during trotting and the hip and tarsal joints during walking (Table 5.3). Significant ($P < 0.05$) differences were found for abduction and adduction joint motion between overground and treadmill-based gaits for the femorotibial joint during trotting and the hip and tarsal joints during walking (Table 5.4).

GIFA—Significant ($P < 0.05$) differences were found among all planes of motion (sagittal [flexion and extension], transverse [internal and external rotation], and frontal [abduction and adduction]) of overground and treadmill-based gaits for the hip, femorotibial, and tarsal joints during both walking and trotting.

Discussion

In the present study, data collection for both overground and treadmill-based gaits produced similar waveform shapes for the hip, femorotibial, and tarsal joints in dogs. However, comparison of these waveforms with 2 methods of waveform analysis provided varied results. Generalized indicator function analysis revealed significant ($P < 0.05$) differences between overground and treadmill-based gaits for all planes of motion and all joints. Fourier analysis revealed no significant differences between overground and treadmill-based gaits for the sagittal plane; however, differences were detected via Fourier analysis for the transverse and frontal planes of motion. The discrepancies between findings obtained via GIFA and Fourier analysis were attributable to fundamental differences in these analyses.[15] Given the distinct similarities among waveform shapes for all joints in dogs of the study reported here, the clinical relevance of these differences is unclear.

To the authors' knowledge, this is the first study to compare complete hind limb kinematic data associated with overground and treadmill-based ambulation for both walking and trotting gaits in dogs. In human medicine, treadmill-based gait assessment is widely used. For research purposes, a distinct advantage is the ability to control variables such as lighting, surface, and velocity.[9,20,21] However, it has been shown that variability exists between overground and treadmill-based gaits of humans during walking[22] and running.[23] In the present study, overground and treadmill-based gaits of dogs produced similar waveform shapes for the hip, femorotibial, and tarsal joints during both walking and trotting. However, the detected variability in the various planes of motion was dependent on the analysis method, indicating that this method is an important factor in assessing differences in kinematic gait waveforms.

Sagittal plane kinematics for the dogs' hip, femorotibial, and tarsal joints were unaffected by mode of ambulation when assessed by Fourier analysis in the present study. This may be explained by the quantitatively larger angular change in the sagittal plane of motion, compared with angular changes in the frontal and transverse planes. Interestingly, the femorotibial joint was the only joint for which no differences between overground and treadmill-based gaits in all planes of motion were found. However, this was only true when the dogs were walking. It is possible that lower treadmill belt speeds may more closely mimic overground ambulation by limiting the effect of belt motion on ambulation.

The effect of marker placement on gait assessment data has been studied. Although overall waveform shapes remain similar, a shift of the waveform in the vertical axis secondary to differences in marker placement can occur.[11,24] Analysis methods such as Fourier analysis can be affected by this translation.15 Therefore, previous studies[11,24] of Fourier analysis have used a normalization procedure to decrease the impact of this shift on subsequent analysis. In the present study, in which no marker loss or reapplication occurred, a normalization procedure was not performed and Fourier analysis revealed no differences in sagittal plane motion. Therefore, the differences detected by GIFA were attributable to variations in the waveform shapes produced during overground and treadmill-based gaits.

In the present study, a limitation was sample size with respect to Fourier analysis of the tarsal joint. The number of dogs used was not adequate to rule out the possibility of generating a type II error in the tarsal joint data analysis, particularly when evaluating all of the coefficients required to reconstruct 95% of the waveform.[11]

Although differences in overground and treadmill-based gaits of humans have been described, it has been argued that if the treadmill belt speed is constant and similar to overground

velocity, then there should be no biomechanical differences between the 2 modes of ambulation.[25] However, results of experimental studies[22,23,26,27] have indicated that differences exist. In 1998, Savelberg et al[27] concluded that intrastride belt-speed variation can lead to kinematic differences between overground and treadmill gaits. Additionally, these differences are related to the overall power of the treadmill and the mass of the subject. In the present study, overground gait data obtained at a predetermined narrow velocity range were accepted for evaluation; however, belt speed was a constant for treadmill-based testing. It is possible that the differences detected by GIFA and, to a lesser extent, Fourier analysis may be secondary to intrastride belt-speed variations or minor differences between a variable overground velocity and constant treadmill belt speed. Further study of such differences is warranted.

Treadmill-based gait has been shown to alter joint range of motion.[26,28] Lee and Hidler[26] evaluated human gaits during overground and treadmill-based walking, and evaluation of sagittal plane kinematics revealed a decreased range of motion for the knees during treadmill walking. This finding is supported by results of another study[28] in humans, which also indicated that there was decreased joint range of motion during treadmill-based gait. Interestingly, Lee and Hidler[26] found very few overall differences between walking overground or on treadmills and concluded that this was attributable to muscular adaptations (modifications in muscle activation and joint moments and powers) that occurred during the treadmill-based gait, which resulted in similar joint kinematics for overground and treadmill ambulation. Similarly, when data obtained from dogs were assessed via Fourier analysis in the present study, no differences were found between overground and treadmill-based gaits during walking for the femorotibial joint. However, this was not true for the hip and tarsal joints. Nevertheless, overall waveform shapes were similar for all 3 joints and all planes of motion during walking and trotting.

Habituation is an integral part of treadmill use for gait analysis. Humans and other animals require sufficient time and training to become accustomed to treadmill-based gaits.[21,22,29] Matsas et al[29] found that for humans, treadmill-based walking could be generalized to overground walking after 6 minutes of treadmill use, indicating that a period of familiarization may be needed to produce comparable gaits. In another study[21] in dogs, a 3-week acclimation period was allowed prior to data collection. In the present study, the dogs were trained for approximately 10 minutes every other day over a period of 2 weeks prior to study initiation, and data acquisition was obtained after 10 seconds of symmetric gait at the predetermined belt speed for walking and trotting. The similarity of resultant waveform shapes for all 3 joints in this study suggested that habituation occurred.

The hypothesis for the present study was supported by the findings. Differences between overground and treadmill-based gaits of dogs were detected; however, the ability to detect differences varied with joint, gait, and analysis method. The results of this study indicated that comparable hind limb kinematic waveform shapes for the hip, femorotibial, and tarsal joints can be acquired from dogs that are walking or trotting overground or on a treadmill. Furthermore, 3-D femorotibial kinematic gait data collected during walking as well as complete hind limb sagittal plane kinematic gait data collected during walking and trotting were comparable. The findings of the present study also confirmed that habituation can occur in the previously reported time frame.[21] However, differences in analysis methods may alter the ability to detect differences between modes of ambulation. Although differences were found between the methods of ambulation in the present study, the clinical relevance of these differences has yet to be elucidated.

Footnotes

a. Vicon Peak Motus L-Frame, Vicon-Peak, Centennial, Colo.
b. Vicon MX03, Vicon Motion Systems Inc, Centennial, Colo.
c. Peak Motus 9.2, Vicon Motion Systems Inc, Centennial, Colo.
d. SAS, version 9.2, SAS Institute Inc, Cary, NC.

References

1. Budsberg SC, Chambers JN, Lue SL, et al. Prospective evaluation of ground reaction forces in dogs undergoing unilateral total hip replacement. Am J Vet Res 1996;57:1781–1785.

2. Budsberg SC, Jevens DJ, Brown J, et al. Evaluation of limb symmetry indices, using ground reaction forces in healthy dogs. Am J Vet Res 1993;54:1569–1574.

3. Budsberg SC, Verstraete MC, Brown J, et al. Vertical loading rates in clinically normal dogs at a trot. Am J Vet Res 1995;56:1275–1280.

4. Budsberg SC, Verstraete MC, Soutas-Little RW. Force plate analysis of the walking gait in healthy dogs. Am J Vet Res 1987;48:915–918.

5. Budsberg SC, Verstraete MC, Soutas-Little RW, et al. Force plate analyses before and after stabilization of canine stifles for cruciate injury. Am J Vet Res 1988;49:1522–1524.

6. Bockstahler BA, Henninger W, Muller M, et al. Influence of borderline hip dysplasia on joint kinematics of clinically sound Belgian Shepherd Dogs. Am J Vet Res 2007;68:271–276.

7. Brebner NS, Moens NM, Runciman JR. Evaluation of a treadmill with integrated force plates for kinetic gait analysis of sound and lame dogs at a trot. Vet Comp Orthop Traumatol 2006;19:205–212.

8. Bockstahler BA, Skalicky M, Peham C, et al. Reliability of ground reaction forces measured on a treadmill system in healthy dogs. Vet J 2007;173:373–378.

9. Clements DN, Owen MR, Carmichael S, et al. Kinematic analysis of the gait of 10 Labrador Retrievers during treadmill locomotion. Vet Rec 2005;156:478–481.

10. Owen M, Richards J, Clements D, et al. Kinematics of the elbow and stifle joints in Greyhounds during treadmill trotting—an investigation of familiarisation. Vet Comp Orthop Traumatol 2004;17:141–140.

11. Hottinger HA, DeCamp CE, Olivier NB, et al. Noninvasive kinematic analysis of the walk in healthy large-breed dogs. Am J Vet Res 1996;57:381–388.

12. Fu YC, Torres BT, Budsberg SC. Evaluation of a three-dimensional kinematic model for canine gait analysis. Am J Vet Res 2010;71:1118–1122.

13. Budsberg SC, Verstraete MC, Reynolds LR, et al. Three dimensional non-invasive kinematics of the canine stifle. Vet Surg 1999;28:387–388.

14. Lu TW, O'Connor JJ. A three-dimensional computer graphics-based animated model of the human locomotor system with anatomical joint constraints. J Biomech 1998;31:116–116.

15. Torres BT, Punke JP, Fu YC, et al. Comparison of canine stifle kinematic data collected with three different targeting models. Vet Surg 2010;39:504–512.

16. Veldpaus FE, Woltring HJ, Dortmans LJ. A least-squares algorithm for the equiform transformation from spatial marker coordinates. J Biomech 1988;21:45–54.

17. Winter DA. Three-dimenstional kinematics and kinetics. In: Biomechanics and motor control of human movement. 4th ed. Hoboken, NJ: Wiley, 2009;183–186.

18. Yokoo T, Knight BW, Sirovich L. An optimization approach to signal extraction from noisy multivariate data. Neuroimage 2001;14:1309–1326.

19. DeCamp CE, Riggs CM, Olivier NB, et al. Kinematic evaluation of gait in dogs with cranial cruciate ligament rupture. Am J Vet Res 1996;57:120–126.

20. Keegan KG, Wilson DA, Wilson DJ, et al. Evaluation of mild lameness in horses trotting on a treadmill by clinicians and interns or residents and correlation of their assessments with kinematic gait analysis. Am J Vet Res 1998;59:1370–1377.

21. Vilensky JA, O'Connor BL, Brandt KD, et al. Serial kinematic analysis of the canine hindlimb joints after deafferentation and anterior cruciate ligament transection. Osteoarthritis Cartilage 1997;5:173–182.

22. Alton F, Baldey L, Caplan S, et al. A kinematic comparison of overground and treadmill walking. Clin Biomech (Bristol, Avon) 1998;13:434–440.

23. Wank V, Frick U, Schmidtbleicher D. Kinematics and electromyography of lower limb muscles in overground and treadmill running. Int J Sports Med 1998;19:455–461.

24. DeCamp CE, Soutas-Little RW, Hauptman J, et al. Kinematic gait analysis of the trot in healthy Greyhounds. Am J Vet Res 1993;54:627–634.

25. van Ingen Schenau GJ. Some fundamental aspects of the biomechanics of overground versus treadmill locomotion. Med Sci Sports Exerc 1980;12:257–261.

26. Lee SJ, Hidler J. Biomechanics of overground vs. treadmill walking in healthy individuals. J Appl Physiol 2008;104:747–755.

27. Savelberg HH, Vorstenbosch MA, Kamman EH, et al. Intra-stride belt-speed variation affects treadmill locomotion. Gait Posture 1998;7:26–34.

28. Watt JR, Franz JR, Jackson K, et al. A three-dimensional kinematic and kinetic comparison of overground and treadmill walking in healthy elderly subjects. Clin Biomech (Bristol, Avon) 2010;25:444–449.

29. Matsas A, Taylor N, McBurney H. Knee joint kinematics from ground walking in young unimpaired subjects. Gait Posture 2000;11:46–53.

Table 5.1. Bilateral marker locations for joint coordinate system kinematic modeling of the hip, femorotibial, and tarsal joints of dogs. (*Marker indicated the origin of the local coordinate system for the specific segment. †Marker was removed during acquisition of dynamic testing data).

Segment	Marker label	Location
Pelvis	†IWG	ilial wing
	ITB	ischial tuberocity
Femoral	†GT	greater trochanter
	LEP	lateral epicondyle
	*MEP	medial epicondyle
	QUA	quadriceps
Tibial	FH	fibular head
	LMA	lateral malleolus
	GAS	gastrocnemius
	†*PTC	proximal tibial crest
	*DTC	distal tibial crest
	*MMA	medial malleolus
Tarsus	†HEE	caudo-lateral calcaneous
	MP5	metatarso-phalangeal #5 joint
	MP2	metatarso-phalangeal #2 joint

Table 5.2. Mean Fourier coefficients derived for the right hip, femorotibial, and tarsal joints of 5 dogs in an assessment of sagittal (flexion-extension) plane kinematics of overground and treadmill-based gaits during walking and trotting.

	Trot						Walk					
	Hip joint		Femorotibial joint		Tarsal joint		Hip joint		Femorotibial joint		Tarsal joint	
Variable	Overground	Treadmill	Overground	Treadmill	Overground	Treadmill	Overground	Treadmill	Overground	Treadmill	Overground	Treadmill
A1	–4.33	–4.71	6.55	6.38	–1.36	–2.27	–4.4	–4.03	4.15	4.42	–2.36	–2.01
A2	0.33	0.1	1.11	2.14	2.35	2.94	2.09	1.98	1.75	1.65	2.43	2.53
A3	–0.16	–0.21	–0.99	–1.38	0.18	–0.28	–0.05	–0.1	–0.74	–0.78	–0.96	–1.06
A4	–0.05	0.08	–0.25	–0.28	–0.15	–0.3	0.03	0.02	–0.25	–0.12	–0.18	–0.25
A5	–0.07	–0.08	–0.04	–0.17	–0.22	–0.1	0.06	0.09	0.02	0.14	–0.18	–0.19
A6	–0.06	–0.03	0	0.12	0.11	0.05	0	–0.02	0	–0.01	0.18	0.27
A7	0	0.01	0.12	0.13	0.13	0.08	–0.02	–0.01	–0.02	0	–0.05	0
A8	0	0	0.06	0.11	0.18	0.06	0.01	–0.02	0	0.04	0.01	0.04
B1	3.47	3.3	3.69	3.73	3.14	2.9	1.02	1.04	3.15	3.2	1.06	1.42
B2	–0.72	–0.8	–5.99	–6.5	–5.49	–5.21	0.36	0.18	–2.08	–2.35	–1.88	–1.79
B3	0.21	0.49	–0.08	0.04	–0.89	–0.71	–0.16	–0.06	–0.79	–0.56	–1.02	–1.3
B4	0	–0.11	0.24	0.15	–0.01	–0.42	0.12	0.02	–0.16	0.05	–0.35	–0.02
B5	–0.1	–0.03	0.12	0.26	–0.22	–0.05	0.04	0.04	0.18	0.11	0.21	0.23
B6	–0.02	–0.03	0.11	0.04	0.07	–0.04	–0.04	–0.04	–0.05	0.01	–0.13	0.05
B7	–0.04	–0.03	–0.03	0	–0.06	–0.03	0.05	–0.01	0.08	0.04	–0.07	–0.11
B8	–0.01	–0.02	–0.02	–0.04	0	0.01	–0.01	–0.01	0.03	0.09	–0.07	0.05

Data are coefficients from the waveforms.

A1–A8 = Cosine coefficients. B1–B8 = Sine coefficients.

Table 5.3. Mean Fourier coefficients derived for the right hip, femorotibial, and tarsal joints of 5 dogs in an assessment of transverse (internal-external rotation) plane kinematics of overground and treadmill-based gaits during walking and trotting.

	Trot						Walk					
	Hip joint		Femorotibial joint		Tarsal joint		Femorotibial joint		Hip joint		Tarsal joint	
Variable	Overground	Treadmill	Overground	Treadmill	Overground	Treadmill	Overground	Treadmill	Overground	Treadmill	Overground	Treadmill
A1	–4.64	–4.76	–1.18	–1.03	0.46	0.79	–4.25	–4.85	–1.97	–1.9	0.87	0.97
A2	0.15	0.09	0.08	–0.91	–1.24	–1.38	–0.37	–0.61	–0.36	–0.75	–0.51	–0.19
A3	0.39	0.24	0.94	0.97	–0.62	–0.54	–0.34	–0.04	–0.12	0.13	–0.11	–0.3
A4	0.13	0.13	–0.3	–0.15	0.09	–0.11	0.19	0.16	0.16	0.2	–0.09	–0.1
A5	–0.02	0.03	0.15	0.28	0.09	0.08	0.09	0.05	–0.25	–0.04	0.14[a]	–0.01[a]
A6	–0.08	0.04	0.09	0.08	0.01	–0.04	0.03	–0.03	0	–0.06	0.02	0
A7	–0.06	0	0.25	0.19	–0.12	–0.09	–0.02	–0.08	0.16	0.19	0.02	0
A8	–0.08	0	0.1	0.11	0.00[b]	–0.12[b]	–0.08	–0.05	0.16	0.11	–0.07	–0.09
B1	2.97	2.19	–1.68	–2.26	–0.52	–0.75	0.32	0.39	0.54	–0.13	–0.78	–0.46
B2	1.34	1.62	–0.38	–0.51	0.25	0.91	–0.29[c]	0.37[c]	0.55	0.77	–0.28	–0.43
B3	0	0.08	–0.4	–0.39	0.48	0.47	0.15	0.56	0.43	0.51	0.15	0.02
B4	0.02[d]	0.45[d]	0.25	–0.44	–0.32	0.07	0.08	0.09	–0.17	0.17	0.1	0.02
B5	–0.08	0.1	0.2	–0.15	–0.17	0.04	0.01	0.02	–0.13	–0.21	0.02	–0.04
B6	–0.23	0	0.21[c]	–0.01[c]	–0.02	0	0.04	0.02	–0.08	0.14	–0.04	–0.03
B7	–0.08[b]	0.07[b]	0.19[a]	–0.04[a]	0.01	–0.04	–0.03	–0.04	0.09	0.15	–0.02	–0.12
B8	–0.03	0	0.02	0.02	0.1	–0.03	0	–0.07	0.02	0.07	–0.09	0.01

[a–d]Values of overground and treadmill-based gait coefficients with the same superscript letter within a row were significantly ([a]P = 0.01; [b]P = 0.02; [c]P = 0.04; and [d]P = 0.002) different.

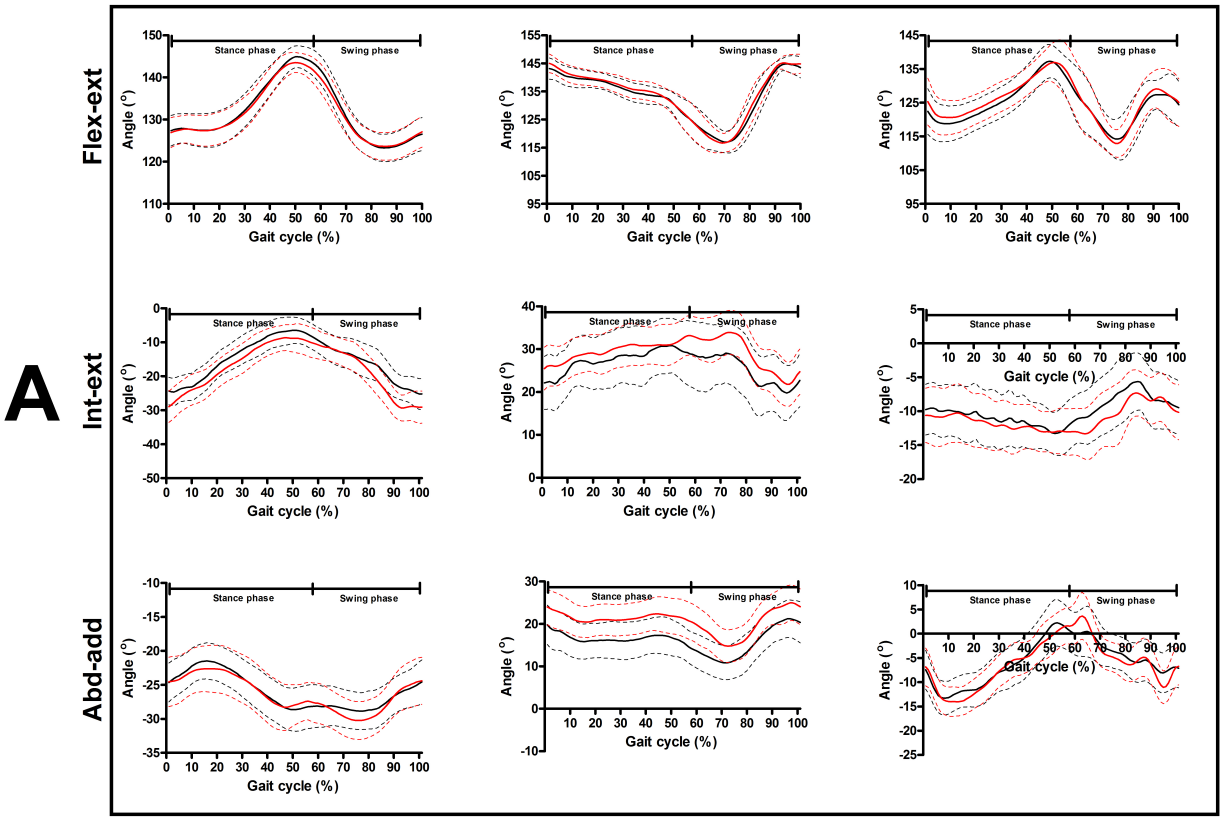
See Table 1 for remainder of key.

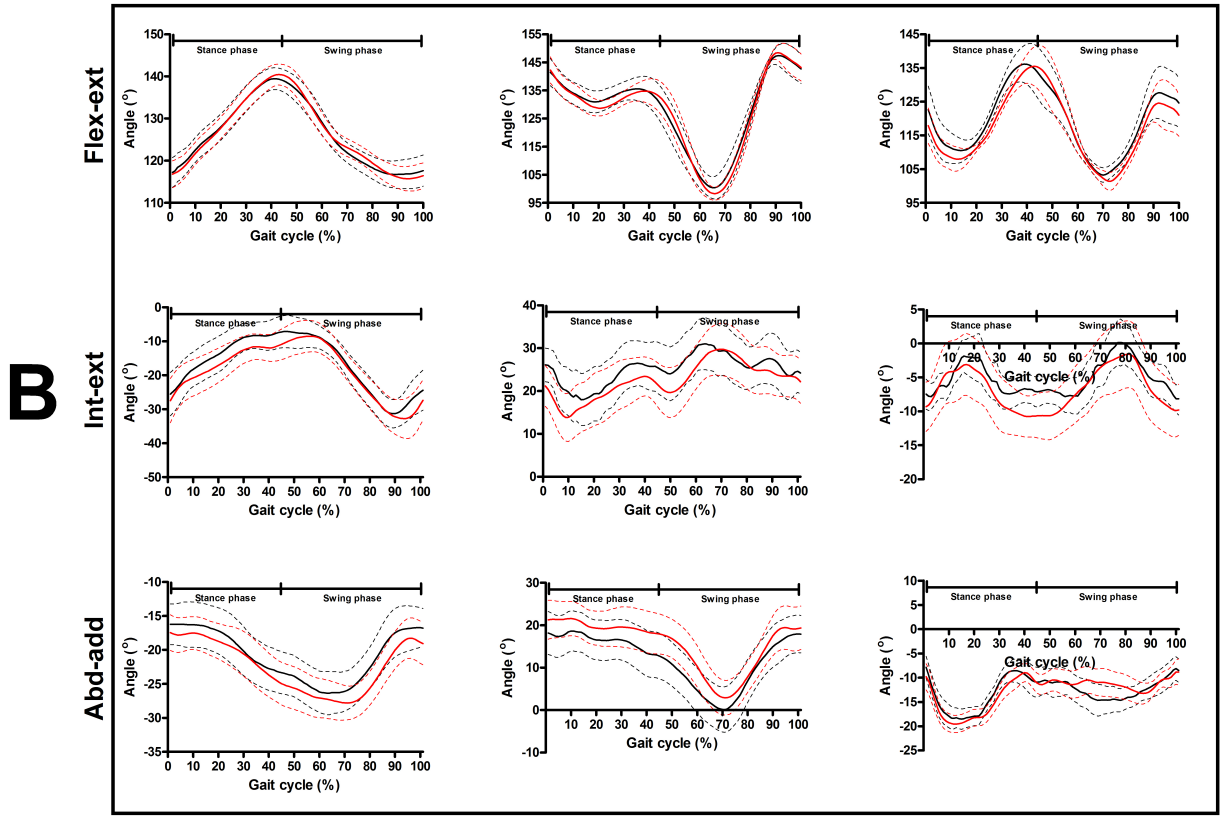
Table 5.4. Mean Fourier coefficients derived for the right hip, femorotibial, and tarsal joints of 5 dogs in an assessment of frontal (abduction-adduction) plane kinematics of overground and treadmill-based gaits during walking and trotting.

	Trot						Walk					
	Hip joint		Femorotibial joint		Tarsal joint		Femorotibial joint		Hip joint		Tarsal joint	
Variable	Overground	Treadmill	Overground	Treadmill	Overground	Treadmill	Overground	Treadmill	Overground	Treadmill	Overground	Treadmill
A1	2.28	2.1	2.42	1.63	–0.68	–1.05	1.03	0.9	0.99	0.65	–2.5	–2.72
A2	0.28	0.34	0.99	1.59	0.9	0.62	–0.15[d]	0.17[d]	1.05	1.2	0.67	0.66
A3	–0.31	–0.07	–0.45	–0.48	0.82	0.92	0.01	0.01	–0.16	–0.16	–0.06	0.29
A4	–0.04	–0.12	–0.06	–0.1	0.25	0.21	–0.12	–0.09	0	–0.11	0.24	0.01
A5	–0.03	–0.09	–0.07	–0.14	0.09	0.23	–0.03	–0.06	0.02	0.08	0.00[a]	0.36[a]
A6	0.01	–0.02	–0.01[c]	–0.08[c]	0.26	0.26	–0.02	–0.02	–0.01	0	0.28	0.33
A7	0	–0.03	0.01	0	0.18	0.04	0.01	–0.02	–0.03	0.01	0.1	0.25
A8	0.03	0.01	0.01	0.03	0.1	0.13	0.01	0.01	–0.02	–0.01	0.24	0.34
B1	1.13	1.49	2.98	3.26	–0.18	–1.11	1.35	1.4	0.64	0.82	–1.71	–1.72
B2	–0.3	–0.19	–1.16	–1.03	–1.42	–1.09	0.45	0.32	–0.95	–0.75	–0.18	–0.07
B3	–0.15	–0.28	–0.27	–0.32	–0.45	–0.17	–0.15	–0.4	–0.38	–0.52	–0.37	–0.62
B4	–0.04	0.01	0.2	0.29	0.14	–0.2	–0.03	0.02	–0.12	0.01	–0.11	0.35
B5	0.09	0.05	0.01	0.05	–0.3	–0.35	–0.04	–0.08	0.05	0.11	–0.04	0.21
B6	0.03	0	–0.19[b]	0.04[b]	–0.08	–0.07	0.01	0	–0.02	0.03	–0.15	–0.04
B7	0.01	0.02	–0.05[b]	0.08[b]	0	–0.03	–0.01	–0.01	–0.02	–0.02	–0.04	0.16
B8	0.01	0.03	–0.02[c]	0.05[c]	–0.03	0.08	0.02	0	–0.02	–0.05	0.03	–0.12

See Tables 1 and 2 for key.

Figure 5.1. Graphs illustrating the mean (solid lines) joint angles with 95% confidence intervals (dashed lines) obtained for the hip (left column), femorotibial (central column), and tarsal (right column) joints of 5 dogs in a study of sagittal (flexion-extension [Flex-ext]), transverse (internal-external rotation [Int-ext]), and frontal (abduction-adduction [Abd-add]) plane kinematics during overground (black lines) or treadmill-based (red lines) ambulation. Quantitative angular change during movement of the distal segment relative to the proximal segment is indicated by the appropriate waveform. A—Values obtained during walking. B—Values obtained during trotting.


A
Flex-ext
Int-ext
Abd-add
Stance phase
Swing phase
Angle (°)
Gait cycle (%)


B
Flex-ext
Int-ext
Abd-add
Stance phase
Swing phase
Angle (°)
Gait cycle (%)

CHAPTER 6

CONCLUSION

Kinematic studies on the canine hindlimb using superficial skin marker systems have become popular in recent decades. However, compared to the extensive three-dimensional (3-D) kinematic studies in human subjects, most studies in veterinary medicine on dogs have been limited to two-dimensions (2-D). In part, this is because of the reduced expense of 2-D kinematic systems. These 2-D systems can obtain accurate and repeatable data in the sagittal plane; however, 2-D systems suffer from parallax error and simultaneous collection of transverse and frontal planes of motion is not possible. The benefit of 3-D systems is their ability to simultaneously collect all planes of joint motion, providing complete 3-D motion data. Previously, 3-D kinematic systems have been used to report uniplanar (sagittal) joint motion in dogs. However, these studies utilized simple linear-link models with laterally applied markers, thus limiting their ability to assess true 3-D joint motion. Until recently, the only 3-D kinematic data in veterinary medicine has been collected with the aid of invasive external fixators, stereo radiographic methods, or in cadaveric models. Recently, a 3-D segmental rigid-body model of the complete hindlimb of a dog has been described. This model utilizes a superficial skin marking system to describe 3-D joint motion by use of 6 independent coordinates or 6 degrees of freedom. The benefit of this type of model is that it provides an anatomically accurate and clinically relevant 3-D description of joint motion with 6 degrees of freedom. The model integrates techniques and algorithms developed for human biomechanical studies, resulting in an advanced biomechanical analysis not previously utilized in veterinary medicine. However, due to

the recent introduction of this model to the veterinary literature there are no studies that compare this new 3-D kinematic model to previously described 2-D models or evaluate the effect of known sources of variability with superficial skin marking systems. Thus, this dissertation sought to address these areas.

Chapter 2 compared the new 3-D model to previously established 2-D models. We found that each model provided useful and repeatable flexion–extension data. However, only the 3-D model provided data from the additional axes of joint rotation. It was not surprising that the 2-D and 3-D models provided similar sagittal plane waveform shapes, as they were collected simultaneously in the dogs. Interestingly, we did find that there were subtle, but significant, differences in the sagittal flexion–extension waveforms of the three models. This was not completely unexpected. While all models share some marker locations, distinct differences are present. Additionally, in regard to waveform analysis, this study introduced a new method of waveform analysis to veterinary medicine. Generalized Indicator Function Analysis and the commonly utilized Fourier analysis both provided the ability to assess differences in waveforms. However, unlike Fourier analysis, which only assesses if the waveforms are similar or dissimilar, GIFA provided the ability to temporally isolate gait differences. This may prove to be a sensitive measure of variability between gait waveforms in which only subtle timing differences occur.

Chapter 3 evaluated marker placement error with the 3-D kinematic model. Simulated marker placement error resulted in detectable differences in gait data. As expected, errors in the horizontal plane (cranial and caudal marker location) resulted in a greater degree of difference than errors in the vertical plane (dorsal and ventral marker location). Additionally, errors in the horizontal plane produced the greatest shift along the y-axis as compared with the anatomically normal position. This study elucidated the concern with reapplication of markers for intraday

testing. Whereas visually similar waveform shapes were attained, variability was detected. Furthermore, overall angular measurement can vary, as is evident by the shifting along the vertical axis. This may prove most important when singular point data is utilized for analysis purposes. Therefore, great care should be taken to provide for secure attachment of all markers to prevent the need for reapplication during testing.

Chapter 4 evaluated the application of the 3-D kinematic model by two different examiners of differing experience and training levels. Intra- and inter-examiner differences were found for both the experienced and novice examiner. Interestingly, while each examiner produced similar waveforms, the extent of differences detected varied according to the analysis method. When data was assessed with GIFA, it was unaltered by experience level while Fourier analysis found that experience reduced variability, reflecting differences inherent to the analysis methods. These findings indicate that consistent and repeatable results from the sagittal plane can be obtained from the kinematic model but experience, and intra- and inter-examiner variability can occur. Despite the use of a 3-D system, data acquisition in the frontal and transverse planes remains inconsistent. Therefore, refinement of the technique is necessary to improve reliability and accuracy in these planes.

Chapter 5 evaluated the 3-D model in dogs during overground or treadmill based ambulation. Differences between overground and treadmill-based gaits of dogs were detected. However, the ability to detect differences varied with joint, gait, and analysis method. The results of this study indicated that comparable hindlimb kinematic waveform shapes for the hip, stifle, and tarsal joints can be acquired from dogs that are walking or trotting overground or on a treadmill. Furthermore, 3-D stifle kinematic gait data collected during walking as well as complete hind limb sagittal plane kinematic gait data collected during walking and trotting were

comparable. This study also confirmed that habituation can occur over a two week period of training. However, differences in analysis methods may alter the ability to detect differences between modes of ambulation. Although differences were found between the methods of ambulation, the clinical relevance of these differences has yet to be elucidated.

This dissertation evaluated a recently described 3-D kinematic model of the hindlimb in dogs with earlier 2-D models. Additionally, previously identified sources of variability in kinematic data collection and analysis were studied. Overall, determination of joint motion was consistent in the sagittal plane but less so in the frontal and transverse planes. It is possible that sources of variability, such as skin motion artifact, may have a more profound effect on these diminutive planes of motion, resulting in increased variability. Regardless, continued refinement of the technique is necessary to improve reliability and accuracy in these planes. This work was performed on normal dogs. Future work should be directed toward the assessment and characterization of joint kinematics in various breeds with differing morphologies, in animals with joint pathology, following surgical or medical therapy, and for the evaluation of rehabilitation techniques. The study of breed morphologic differences and their effect on joint kinematics is an important topic for future studies as there is substantial variation in musculoskeletal morphology in the dog population and it is anticipated that these variations will impact analyses. In addition, the effect of orthopedic procedures on joint kinematics is unknown. Enlightenment in this area would prove beneficial to our understanding, and refinement, of surgical procedures. Furthermore, the area of post-therapy rehabilitation is expanding in veterinary medicine and the use of kinematic assessment should prove valuable in the evaluation of patient progress during the rehabilitation period and refinement of therapeutic techniques.