INTRODUCTION
Pathological and injured gaits often produce limb asymmetry, which can be used to identify and track problems [1]. Shorter et al. addressed this by developing the Regions of Deviation (ROD) method for identifying regions of the gait cycle where joint angular displacements deviated from normative data [2]. To statistically identify differences, Shorter et al. performed a $t$-test at single points during stance and swing. Our goal was to extend their statistical analysis by utilizing point-wise $t$-tests on the deviation data throughout the entire gait cycle to get a sense of the true regions for which the movement patterns deviated from normal. We demonstrate these methods on canine gait data of Labrador Retrievers without and with naturally occurring cranial cruciate ligament disease (CCLD) in the hind limb. The CCL is a critical stifle (knee) stabilizer and CCLD is the leading cause of pelvic lameness in dogs. ROD methodology results on these dogs were then compared to the kinematic peak difference analysis described in [3].

METHODS
Twenty-one adult pure bred Labrador Retrievers (36.6 ± 8.5 kg, 81 ± 30 months, 13 females/8 males) were used. Twelve were healthy and 9 had unilateral hind limb CCLD. Data collection and inverse dynamics computation were previously described [3,4]. Sagittal-plane projections of joint angular displacements for the hip, stifle (knee), and hock (ankle) joints of both hind limbs were examined. Data were linearly time normalized from 0-100% gait cycle at 1% increments, and separated into stance and swing. Both phases were normalized again so that toe-off consistently occurred at 46% GC, which was the healthy group average.

Since this work focused on deviations from symmetry, analysis was performed on the magnitude of differences between the left ($l$) and right ($r$) joint angles ($V$). The absolute difference for each joint ($j$) of subject $i$ was defined as

$$
\Delta V_{j,n}^{(i)} = |V_{j,n}^{(i,l)} - V_{j,n}^{(i,r)}|
$$

for each $n$, corresponding to percent gait cycle. The deviation from normative data ($D$) was defined as

$$
D_{j,n}^{(i)} = \begin{cases} 
\Delta V_{j,n}^{(i)} - N_{j,n} & \text{if } \Delta V_{j,n}^{(i)} > N_{j,n} \\
0 & \text{if } \Delta V_{j,n}^{(i)} \leq N_{j,n}
\end{cases}
$$

where $N_{j,n} = \Delta V_{j,n} + SD_{j,n}$, such that the corresponding healthy group mean and standard deviation are $\Delta V_{j,n}$ and $SD_{j,n}$, respectively. Paired $t$-tests were performed ($\alpha = 0.05$) at every point $n$ (1% GC) of $D$ between groups for each joint. All points $n$ found to be significant were then considered to fall within a region of deviation from symmetry for joint $j$.

Discriminant function analysis (DFA) was used to validate that these discrete regions of deviation were better discriminators of differences between healthy and CCLD behavior than using the entire cycle. Subjects were classified with the holdout method as either healthy or having CCLD. These classification results were then compared to similar results using all time points (rather than just regions of deviation) to see whether the ROD methodology improved the classification.

RESULTS and DISCUSSION
Average CCLD affected and contralateral limb joint angle patterns were qualitatively quite different from the average normal limb (Fig.1a-c). The major peaks previously analyzed by [3] are labeled for reference and comparison. The asymmetries induced by CCLD were also readily apparent; significant regions of deviation from symmetry, as compared to the healthy group, are indicated by shading (Fig.1d-f).
Comparing significant peak differences from [3] to the shaded regions of deviation was the first step in assessing the additional information provided by the new ROD methodology. Significant peak differences (between affected and contralateral limbs) found in [3] were hock flexion in stance (Ho2) and stifle flexion in swing (S3). Current results found regions of deviation at those peak locations, as well as at peak swing-phase extension and flexion of the hock (Ho3 and Ho4, respectively), and peak swing extension and flexion of the hip (H2 and H3, respectively). These additional peaks within the regions of deviation suggested that their asymmetry was significantly affected, while peak values between individual limbs were not. Thus, studying differences of limb asymmetry between healthy and CCLD groups (rather than differences between affected and contralateral limbs of the injured group) uncovers additional insight to the effects of the disease.

An additional benefit to using the ROD methodology is to provide the assessment of symmetry beyond that of traditionally only examining peak values such as in [3]. This was especially prevalent in the hock and stifle angle differences, where the regions of deviation encompassed wide areas around the significant peaks. Timing offsets (in addition to those compensated for by normalizing stance and swing) can also be uncovered in these regions. For example, the shaded region around peak S3 appears to be caused by a timing shift between the affected and contralateral limbs.

DFA was used to assess whether the regions of deviation were truly areas of the gait cycle needing focus. DFA using only the identified regions of deviation as input classified all but two subjects correctly (one from each group), whereas DFA using all time points throughout the gait cycle classified four subjects incorrectly (one healthy and three CCLD). Therefore, using the regions of deviation data, instead of all time points, decreased the DFA classification error, suggesting that the ROD methodology is a viable approach for distinguishing differences in motion patterns.

CONCLUSIONS

ROD analysis using t-tests provides a unique opportunity to focus gait analysis on regions of the gait cycle that demonstrate significant asymmetry. This study successfully demonstrated how the new method expanded analysis outside of predetermined areas of interest such as peak differences, thus identifying regions of significance throughout the gait cycle. Further focusing on asymmetry magnitudes between limbs, rather than only assessing unilateral group means, may provide new insight into abnormal gait patterns. This work suggests that these sections (regions) during gait should be examined more thoroughly. These significant times and asymmetry magnitudes can then help researchers and clinicians understand the mechanisms behind lameness and compensation.

REFERENCES


ACKNOWLEDGEMENTS

National Science Foundation, grant #0727083, and American Veterinary Medical Foundation.