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PAPER

Aquatic treadmill water level influence on pelvic limb kinematics in cranial cruciate ligament-deficient dogs with surgically stabilised stifles

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Objective: To compare pelvic limb joint kinematics and temporal gait characteristics during land-based and aquatic-based treadmill walking in dogs that have undergone surgical stabilisation for cranial cruciate ligament deficiency.

Materials and Methods: Client-owned dogs with surgically stabilised stifles following cranial cruciate ligament deficiency performed three walking trials consisting of three consecutive gait cycles on an aquatic treadmill under four water levels. Hip, stifle and hock range of motion; peak extension; and peak flexion were assessed for the affected limb at each water level. Gait cycle time and stance phase percentage were also determined.

Results: Ten client-owned dogs of varying breeds were evaluated at a mean of 55·2 days postoperatively. Aquatic treadmill water level influenced pelvic limb kinematics and temporal gait outcomes. Increased stifle joint flexion was observed as treadmill water level increased, peaking when the water level was at the hip. Similarly, hip flexion increased at the hip water level. Stifle range of motion was greatest at stifle and hip water levels. Stance phase percentage was significantly decreased when water level was at the hip.

Clinical Significance: Aquatic treadmill walking has become a common rehabilitation modality following surgical stabilisation of cranial cruciate ligament deficiency. However, evidence-based best practice guidelines to enhance stifle kinematics do not exist. Our findings suggest that rehabilitation utilising a water level at or above the stifle will achieve the best stifle kinematics following surgical stifle stabilisation.

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INTRODUCTION

Cranial cruciate ligament (CrCL) deficiency is one of the most common orthopaedic conditions and is the leading cause of lameness in the canine stifle, with a prevalence of over 2·5% across all breeds (Johnson *et al.* 1994, Witsberger *et al.* 2008). Rupture of the CrCL leads to stifle instability, inflammation, pain and osteoarthritis (Arnoczky & Marshall 1977, Cook 2010). CrCL deficiency was estimated to have an economic impact exceeding $1·3 billion annually in the USA in 2003 (Wilke *et al.* 2006). However, the cause of CrCL deficiency remains unknown (Griffon 2010), is rarely the result of trauma (Cook 2010) and is likely the result of a multi-factorial degenerative process (Cook 2010, Griffon 2010). Larger breed dogs are less likely to return to normal function following CrCL deficiency without corrective stifle stabilisation (Vasseur 1984); subsequent medial meniscus injury can also occur (DeCamp *et al.* 1996, Hayes *et al.* 2010). Therefore, surgical intervention is often employed to stabilise the stifle, but no surgical procedure has been universally accepted with evidenced-based support for long-term success, osteoarthritis prevention or superiority over other procedures (Moore & Read 1995, Aragon & Budsberg 2005, Lopez 2010).

Canine gait is typically altered following CrCL deficiency due to stifle instability and compensation at the hip and hock joints (DeCamp *et al.* 1996). Land-based walking showed that braking and vertical ground reaction forces as well as stifle extension at push-off are reduced in the CrCL-deficient pelvic limb (Ragetly *et al.* 2010). Furthermore, following stabilisation of CrCL deficiency with tibial plateau levelling osteotomy, loss of more than 10° of stifle flexion or extension was significantly correlated with higher clinical lameness scores, while loss of stifle flexion or extension less than 10° was not significantly correlated with higher clinical lameness scores (Jandi & Schulman 2007). Maintaining similar preinjury stifle range of motion (ROM) and gait kinematics may therefore reduce the likelihood for lameness and supports the need for effective rehabilitation following CrCL deficiency.

Aquatic rehabilitation therapies, such as swimming and aquatic treadmill walking, are modalities commonly used during recovery from orthopaedic surgery. The benefits of aquatic therapy have been demonstrated in dogs with a surgically–stabilised stifle following CrCL rupture; these dogs achieved greater active stifle and hock joint ROM while swimming compared to walking on a land-based treadmill (Marsolais *et al.* 2003). Additionally, other studies incorporating aquatic therapy into their rehabilitation programmes indicated significantly larger thigh circumference, greater stifle ROM and improved overall joint function (Millis *et al.* 1997, Bockstahler *et al.* 2002, Marsolais *et al.* 2003, Monk *et al.* 2006). When using an aquatic treadmill, as water level increases, total weight bearing is reduced. Water levels at the greater trochanter, stifle and hock led to 38%, 85% and 91% of land-based weight in dogs, respectively (Tragauer & Levine 2002). Healthy dogs walking on an aquatic treadmill typically have the greatest pelvic limb joint flexion when the water level is at or above the stifle joint, while full extension was typical for the ground-based and hock water levels (Millis & Levine 2014). To our knowledge, the effects of aquatic treadmill water level on CrCL-deficient canine pelvic limb kinematics have not been described.

The objective of this study was to compare pelvic limb joint kinematics and temporal gait characteristics across land-based and aquatic-based treadmill walking in dogs that have undergone surgical correction for unilateral CrCL deficiency. Our hypothesis was that stifle joint ROM would increase with increased aquatic treadmill water level. Our goal was to provide support for evidence-based decision making in rehabilitation strategies following surgical repair of CrCL deficiency.

MATERIALS AND METHODS

Animals

Ten client-owned dogs that had previously undergone unilateral CrCL corrective surgery were recruited for this study. The study protocol was approved by the University of Louisville Institutional Animal Care and Use Committee (IACUC), and owners provided informed consent for their dog's participation in the study. A combined intracapsular/extracapsular stifle stabilisation surgical procedure was previously performed by two board-certified veterinary surgeons from the same specialty hospital. Dogs were excluded from the study if neurological or orthopaedic abnormalities other than prior unilateral CrCL corrective surgery were present. Canine subject signalment, weight, height, medications, surgical date and medical history were obtained.

Gait trials

High-contrast reflective markers were placed on the skin surface of the affected limb at the distal lateral aspect of the fifth metatarsal, lateral malleolus of the tibia, stifle joint between the lateral epicondyle of the femur and the fibular head, greater trochanter of the femur and the cranial dorsal iliac crest (Fig 1). Hair was clipped over the anatomic landmarks, and the markers were adhered to the skin. Markers were positioned on each dog by the same individual (KB). A single video camera (AG-DVC30, Panasonic) recording at 60 Hz was positioned perpendicular to the treadmill long axis and sagittal plane of the canine subject to capture the affected pelvic limb kinematics. The motion capture system was calibrated using a calibration frame of known dimensions.

An aquatic treadmill (Therapy-For-Dogs) with adjustable water level, treadmill velocity and treadmill height was used during walking trials. Subjects completed walking trials for four different water levels [water level superimposed with the marker at the hip joint, stifle joint and hock joint, and land-based (=no water)] at a constant speed of 0·45 m/s (1·0 mph). Treadmill velocity was chosen such that all dogs could comfortably ambulate, and the velocity was confirmed using a reference point on the treadmill belt, along with a known belt length and the digital time code on the recorded video footage. The order of water level testing conditions was randomised across subjects; all subjects performed trials at each water level. Each trial consisted of three consecutive gait cycles, and three trials were completed for each water level (nine total steps per water level). Subjects were acclimated to treadmill speed, water temperature and enclosure before testing and were provided a 5-minute resting period between each test condition. Water temperature was maintained between 31·1 and 32·8°C (88 and 91°F). Subjects were monitored during trials, and a handler maintained subject alignment parallel to the treadmill long axis using a loose slip lead. If the subject moved fore or aft more than 10 cm during a given cycle,

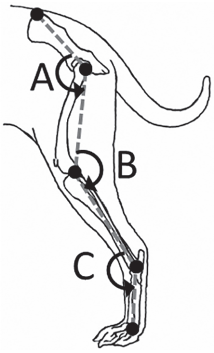

FIG 1. Canine pelvic limb marker locations and the measurement protocol for hip (A), stifle (B) and hock (C) joint angles

the trial was excluded from analysis. Signs of exhaustion, pain or distress during trials led to exclusion from the study.

Gait analysis

Sagittal plane reflective marker coordinate positions were manually digitised for each gait cycle using motion tracking and analysis software (MaxTraq, Innovision Systems, Inc.). A fourth-order, low-pass digital Butterworth filter (6 Hz cutoff frequency) was used to filter signals. Hip, stifle and hock joint ROM; peak extension; and peak flexion were determined. Peak extension was defined as the maximum joint angle recorded in a gait cycle, and peak flexion was defined as the minimum joint angle recorded in a gait cycle. Hip, stifle and hock joint angles (Fig 1) were measured following the protocol previously defined by Jaegger *et al.* (2002) using the marker set described above. Gait cycle time and stance phase percentage (percentage of the total gait cycle corresponding to stance) were also assessed. Stance and swing phases were visually determined by paw placement on the treadmill. The frame numbers corresponding to paw down and paw off were recorded and used to divide the gait cycle into stance and swing.

Data analysis

Descriptive statistics were used to present signalment data and number of days after surgery. The Shapiro–Wilk test was used to determine whether outcome measures significantly differed from a normal distribution. When assumptions of normality and homogeneity were met, kinematic data, cycle time and stance phase percentage for three trials, each containing three gait cycles, were averaged, and a repeated measures analysis of variance (ANOVA) was used to compare outcome measures across the four water levels. For each comparison, Mauchly's test was performed to evaluate the assumption that variances of the differences between conditions were equal (sphericity). For instances where Mauchly's test indicated the assumption of sphericity was not met, degrees of freedom were corrected using Greenhouse–Geisser estimates of sphericity, and corrected degrees of freedom were reported. Height and weight were evaluated for correlations with outcome measures and were implemented as covariates in the analysis as appropriate. *Post hoc* tests using Bonferroni correction were performed to test for differences between the four water levels. Statistical significance was established as $P<0{\cdot}05$.

RESULTS

Signalment

Ten dogs (four neutered male, five spayed female, one intact female) with a mean age of 8 years [95% confidence interval (CI): 5·2 to 10·8], weighing a mean of 20·1 kg (95% CI: 12·1 to 28·1) and with a mean height to the withers of 49·1 cm (95% CI: 39·3 to 59·0) were included in this study. Subjects represented various breeds (four Labrador retrievers, one Alaskan malamute, one beagle, three terriers and one mixed breed). Dogs were evaluated for an average of 55·2 days (95% CI: 26·9 to 83·5) after stifle stabilisation for CrCL deficiency. One dog was receiving maintenance non-steroidal anti-inflammatory medications during the study. Two dogs received less than two rehabilitation sessions after CrCL deficiency surgical management. All dogs were undergoing home therapy consisting of passive ROM and leash walking.

Kinematics

Affected pelvic limb mean peak joint extension (maximum joint angle) during gait did not vary across water level for the hock ($P=0{\cdot}391$), stifle ($P=0{\cdot}318$) or hip ($P=0{\cdot}486$). Mean hock joint minimum angle likewise did not vary across water level ($P=0{\cdot}066$). Mean stifle joint minimum angle (103·5°) was significantly higher, indicating less flexion, for the land-based water level compared to the hip (76·0°; $P=0{\cdot}000$), stifle (82·6°; $P=0{\cdot}002$) and hock (87·8°; $P=0{\cdot}005$) water levels. Mean stifle joint minimum angle was also significantly higher (less flexion) for the hock water level compared to the hip water level (87·8° *versus* 76·0°; $P=0{\cdot}020$). Mean hip joint minimum angle at the hip water level (91·7°) was significantly lower, indicating greater flexion, compared to the stifle (105·1°; $P=0{\cdot}005$), hock (103·3°; $P=0{\cdot}006$) and land-based (108·6°; $P=0{\cdot}007$) water levels (Table 1).

Hock ROM was significantly greater at the hock water level as compared to the land-based water level (46·6° *versus* 32·1°; $P=0{\cdot}032$). Stifle ROM at the stifle water level (61·2°) was significantly greater as compared to the hock (54·2°; $P=0{\cdot}014$) and land-based (42·3°; $P=0{\cdot}001$) water levels. Stifle ROM at the land-based water level (42·3°) was also significantly lower than at the hock (54·2°; $P=0{\cdot}011$) and hip (64·8°; $P=0{\cdot}015$) water levels. Dog

Table 1. Affected pelvic limb hip, stifle and hock joint mean peak flexion and extension with 95% confidence intervals for all subjects at four treadmill water levels

Joint	Measure	Water level condition			
		Hip	Stifle	Hock	Land
Hip	Peak flexion (°) (minimum joint angle)	91·7 [81·8 to 101·6]*	105·1 [98·3 to 112·0]	103·3 [97·4 to 109·1]	108·6 [102·7 to 114·4]
	Peak extension (°) (maximum joint angle)	139·9 [127·9 to 151·8]	139·7 [130·6 to 148·9]	138·4 [130·4 to 146·3]	136·4 [129·3 to 143·6]
	Range of motion (°)	48·1 [36·7 to 59·5]*	34·6 [26·5 to 42·7]	35·1 [27·3 to 42·9]	27·9 [24·4 to 31·4]
Stifle	Peak flexion (°) (minimum joint angle)	76·0 [64·2 to 87·7]†	82·6 [72·0 to 93·2]	87·8 [81·2 to 94·3]†	103·5 [93·4 to 113·6]*
	Peak extension (°) (maximum joint angle)	140·8 [129·5 to 152·0]	143·8 [133·6 to 153·9]	141·9 [132·9 to 150·9]	145·8 [135·8 to 155·9]
	Range of motion (°)	64·8 [54·6 to 75·0]	61·2 [54·3 to 68·1]†	54·2 [47·4 to 61·0]†	42·3 [36·8 to 47·8]*
Hock	Peak flexion (°) (minimum joint angle)	117·3 [104·7 to 129·9]	115·0 [104·7 to 125·3]	112·0 [101·8 to 122·1]	121·9 [112·2 to 131·7]
	Peak extension (°) (maximum joint angle)	159·1 [148·4 to 169·7]	158·1 [150·6 to 165·7]	158·5 [151·6 to 165·5]	154·0 [147·5 to 160·6]
	Range of motion (°)	41·8 [33·8 to 49·8]	43·1 [34·9 to 51·3]	46·6 [36·0 to 57·2]†	32·1 [23·7 to 40·5]†

*Significant difference from all other water level conditions
†Significant difference between water level conditions

height correlated with hip ROM and was included as a covariate. Hip ROM at the hip water level (48·1°) was significantly greater as compared to the stifle (34·6°; P=0·016), hock (35·1°; P=0·032) and land-based (27·9°; P=0·016) water levels (Fig 2).

Stifle joint angle during stance and swing differed across water levels (Fig 3). Stifle flexion increased during swing as water level increased, while stifle extension decreased during stance for the land-based, hock and stifle water levels. Stifle extension was similar at the start and end of stance for the hip water level. Finally, following maximum stifle flexion, stifle extension peaked in late swing for the land-based water level but peaked during early stance for the hock, stifle and hip water levels.

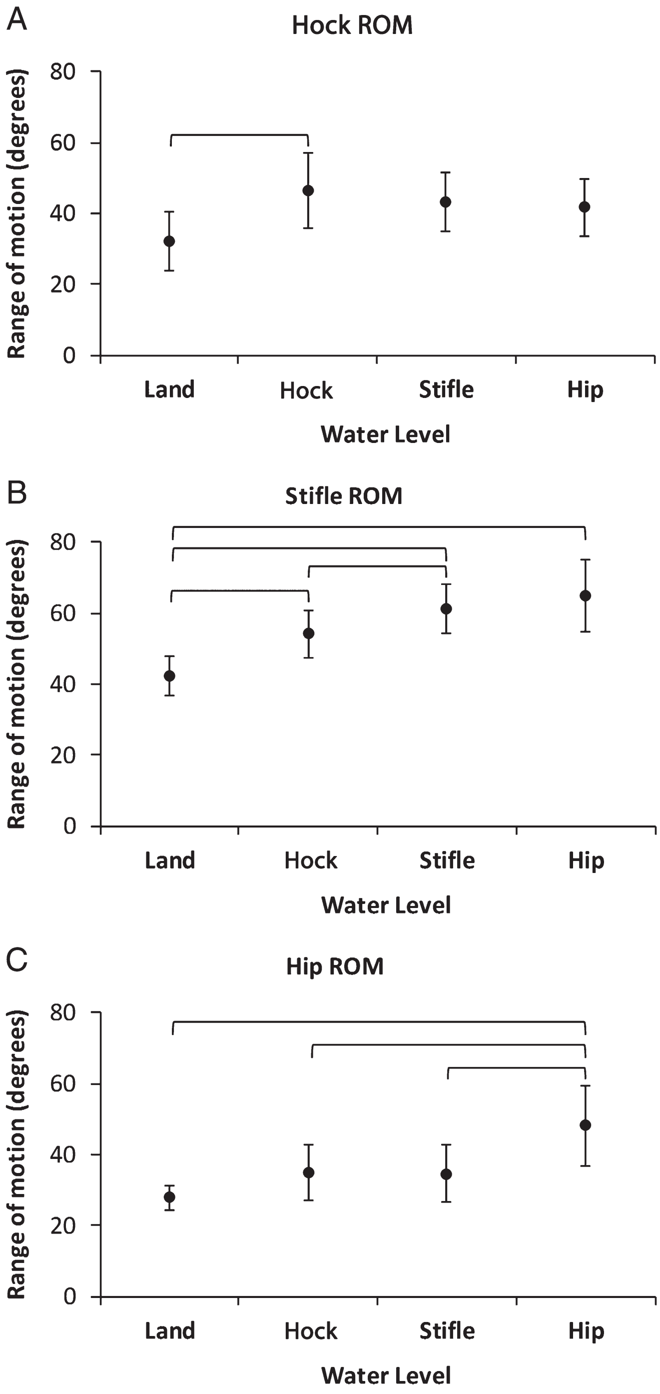

FIG 2. (A) Overall group mean affected limb hock range of motion (ROM) *versus* water level (n=10). (B) Overall group mean affected limb stifle ROM *versus* water level (n=10). (C) Overall group mean affected limb hip ROM *versus* water level (n=10). Error bars represent 95% confidence intervals. Horizontal brackets indicate significant differences between water levels

Gait temporal characteristics

Dog height and weight correlated with gait cycle time at all water levels and were included as covariates. Gait cycle time for the land-based water level (1·0 second) was significantly lower as compared to the hock (1·2 seconds; P=0·000) and stifle (1·2 seconds; P=0·000) water levels. The stance phase percentage was significantly higher at the hock water level than at the hip water level (0·7% *versus* 0·5%; P=0·008), indicating greater paw contact with the treadmill belt at the hock water level. However, stance phase percentage was significantly lower for the hock water level than the land-based water level (0·6% *versus* 0·7%; P=0·022). Likewise, stance phase percentage at the stifle water level (0·6%) was significantly higher than at the hip water level (0·5%; P=0·003) and significantly lower than at the land-based water level (0·7%; P=0·007). There was no significant difference in cycle time (1·2 seconds *versus* 1·2 seconds; P=1·000) or stance phase percentage (0·6% *versus* 0·6%; P=1·000) between the hock and stifle water levels (Fig 4).

DISCUSSION

In general, our findings indicated that aquatic treadmill water level influenced temporal gait characteristics. As the water level increased, gait cycle time increased and stance phase percentage decreased, likely due to additional buoyancy and fluid resistance. These findings, which are consistent with another study (Mendez-Angulo *et al.* 2013), are important to the rehabilitation process since reducing the stance phase may help decrease impact on pelvic limb joints by limiting ground contact. Although other studies reported that stance time and stride length were greater in dogs walking on a land-based treadmill as compared to over ground walking (Schwartz *et al.* 2004), our study illustrated that the land-based treadmill stance phase percentage can be significantly reduced by introducing water at any joint level.

Joint ROM was found to be greater for the hip, stifle and hock water levels compared to the land-based water level. Similar findings were reported in healthy horses walking on an aquatic treadmill at different water depths (Mendez-Angulo *et al.* 2013), and as also found in the current study, increased ROM was primarily due to changes in joint flexion (Mendez-Angulo *et al.* 2013). Treadmill conditions significantly influenced stifle ROM, confirming our hypothesis. Stifle ROM increased as water level increased, with stifle and hip water levels leading to the greatest stifle ROM (61·2° and 64·8°, respectively). Improved stifle ROM has been shown to reduce the likelihood of lameness in the CrCL-deficient pelvic limb (Jandi & Schulman 2007). Rehabilitation using an aquatic treadmill with the water level at the stifle or hip may therefore help maximise stifle ROM and negate decreased ROM from

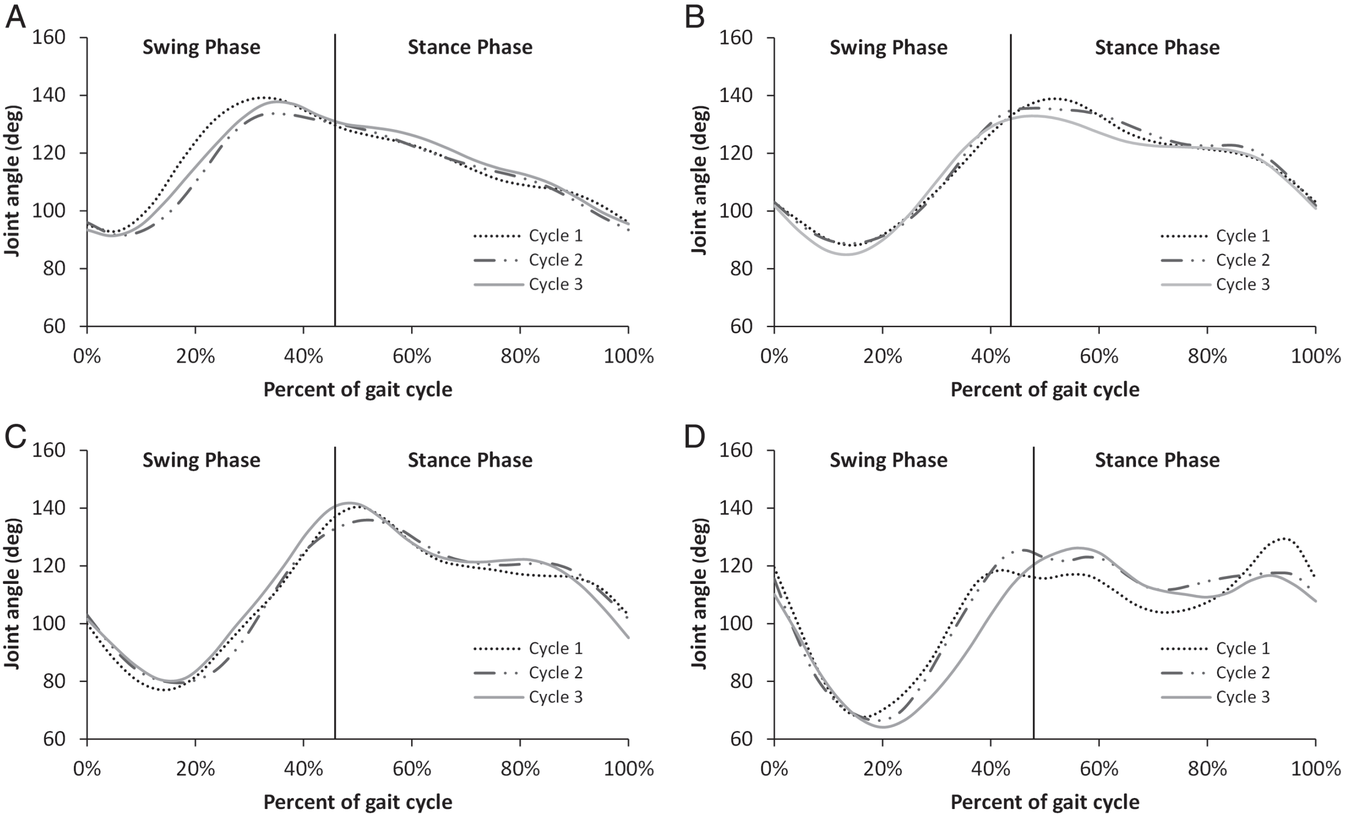

FIG 3. Stifle joint angle during the swing and stance phases of gait for a representative dog. One trial consisting of three gait cycles is shown for the land-based (A), hock (B), stifle (C) and hip (D) water levels. The vertical line separates the swing and stance phases

CrCL deficiency (DeCamp *et al.* 1996). Furthermore, stifle pain may be reduced due to decreased vertical ground reaction force associated with buoyancy effects (Tragauer & Levine 2002), and reduced weight bearing may help prevent stifle instability and pain induced by cranial tibial thrust (Ragetly *et al.* 2010). Although the stifle was our primary focus, we found that hip and hock ROMs were also influenced by water level. Hip ROM at the hip water level (48·1°) was significantly greater than at all other water levels, while hock ROM was significantly increased (46·6°) at the hock water level compared to the land-based water level (32·1°).

It is difficult to compare ROM across studies given differences in dog size and breed, as well as differences in walking speed. However, it appears that hip, stifle and hock ROM for the land-based water level in our study were similar to those found by Holler *et al.* (2010) for CrCL-intact dogs walking at 1·2 m/s on a treadmill as well as those found by Hottinger *et al.* (1996) for CrCL-intact dogs walking at 1·0 m/s over ground (Table A1). Interestingly, hip and stifle ROM (48·1° and 64·8°, respectively) achieved at the hip water level were similar to CrCL-intact subjects trotting at 2·87 m/s over ground (45·7° and 65·9°; Table A1) (Gillette & Zebas 1999). Moreover, stifle ROM at the hip water level (64·8°) was also similar to treadmill trotting at 2·0 m/s in CrCL-intact dogs (61·3°; Table A1) (Clements *et al.* 2005). Our findings also show that hip and stifle ROM (48·1° and 64·8°, respectively) achieved at the hip water level were similar to those of CrCL-intact subjects while swimming (~45° and ~66°) (Marsolais *et al.* 2003). However, swimming has been associated with less stifle and hock extension in both healthy dogs and dogs that have undergone extracapsular stabilisation as compared to walking on a land-based treadmill (Marsolais *et al.* 2003). Interestingly, dogs in our study achieved a stifle extension of ~141° at the hip water level, while healthy dogs and dogs with extracapsular stabilisation only achieved stifle extension of ~113° and ~94°, respectively, during swimming in a study by Marsolais *et al.* (2003) (Table A1). Thus, maximum extension achieved by healthy dogs during swimming was exceeded by surgically stabilised dogs walking on an aquatic treadmill with water at the hip level. This suggests that aquatic treadmill therapy may be more effective in returning full stifle extension than swimming. Walking on an aquatic treadmill with hip water level can also potentially achieve pelvic limb joint angles found in healthy dogs trotting at higher speeds (Gillette & Zebas 1999) and ROMs similar to swimming (Marsolais *et al.* 2003). Since CrCL-deficient dogs recovering from stifle stabilisation surgery may take considerable time to achieve trotting at higher speeds, the aquatic treadmill may provide an effective means of attaining similar benefits of increased ROM associated with fast trotting and swimming while maintaining stifle extension not achievable through swimming. In healthy dogs walking on an aquatic treadmill, maximum pelvic limb extension was typical for the ground-based and hock water levels (Millis & Levine 2014). No significant reduction in peak joint extension (maximum angle) occurred at any water level compared to the land-based water level, suggesting that maximum extension was preserved in underwater treadmill walking. However, stifle joint

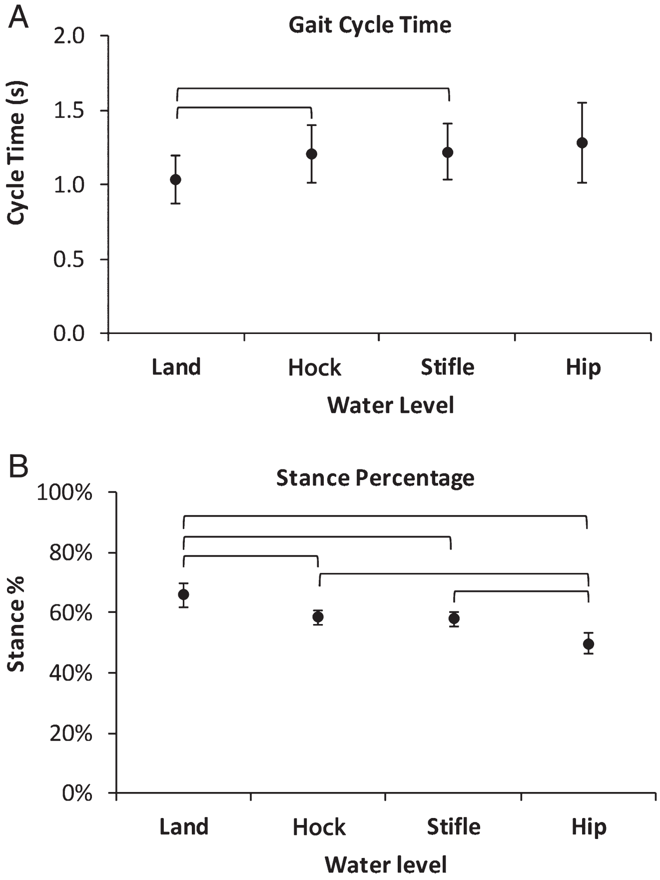

FIG 4. (A) Overall group mean affected limb gait cycle time *versus* water level (n=10). (B) Overall group mean affected limb stance phase percentage *versus* water level (n=10). Error bars represent 95% confidence intervals. Horizontal brackets indicate significant differences between water levels

flexion (minimum angle) significantly increased at all water levels compared to the land-based water level, highlighting the benefits of the aquatic treadmill for rehabilitation.

Peak stifle joint flexion consistently occurred during the mid-swing phase of gait. As water level increased, dogs likely became more buoyant, leading to a longer swing phase that might have enabled greater stifle flexion. Similar increased pelvic limb joint flexion was reported in healthy dogs walking on an aquatic treadmill when the water level was at the stifle joint (Millis & Levine 2014). It is postulated that buoyancy may aid in upward or dorsally directed limb segment motion, thereby assisting in elevating the thigh, crus or both, and decreasing effort needed to flex the hip, stifle or both.

Our findings suggest the use of an aquatic treadmill as part of a rehabilitation programme may help optimise stifle joint biomechanics following surgical stabilisation. Our study was limited to dogs with intracapsular/extracapsular stifle stabilisation. Findings may differ for dogs receiving other surgical stabilisation procedures. In one study, stifle and hock joint angles during trotting gait in dogs with CrCL-intact stifles were unchanged when compared to the same dogs receiving tibial plateau levelling osteotomy following CrCL transection (Lee *et al.* 2007). However, stifle and hock joint angles differed from CrCL-intact kinematics in dogs receiving cranial tibial wedge osteotomy following CrCL transection (Lee *et al.* 2007).

Our analysis evaluated sagittal plane pelvic limb kinematics. Two-dimensional pelvic limb sagittal plane gait analysis has been shown to compare favourably with three-dimensional analysis (Kim *et al.* 2008). However, pelvic limb internal–external rotation and abduction–adduction were not assessed in this study, and the effects of water level on these measures were not determined. Water movement and refraction may have influenced perceived marker locations and thus reported joint angles. This effect was most likely to occur for markers positioned at the water level. However, given that our joint angle findings were comparable to those reported in other studies, perceived marker locations were likely reasonably accurate. Another study evaluating kinematics of horses on an aquatic treadmill reported that error due to refraction of light in water was less than 3° (Mendez-Angulo *et al.* 2013). Our study was limited by the small sample of dogs evaluated; a larger sample may have influenced outcomes. Moreover, we included varying breeds, whereas breed and size homogeneity may have decreased variability in outcomes. For example, in our study, treadmill speed was constant for all trials, and temporal gait characteristics may differ across breeds of different sizes at a single speed. To account for this possibility, potential covariates, including dog height and weight, were evaluated for correlations with all outcome measures in our study. Not surprisingly, it was determined that height and weight correlated with gait cycle time at all water levels. Larger breed dogs would be expected to complete a gait cycle more slowly than smaller breed dogs when walking at the same speed. Additionally, height correlated with hip ROM. Statistical analyses were adjusted accordingly for these covariates. Subjects in this study were evaluated at a mean of 55·2 days post-operatively. It is expected that evaluation at another time point could generate differing outcomes. The extent and compliance of home therapy conducted by owners was not controlled for in this study. It is anticipated that consistency of home therapy or the lack thereof may have an effect on gait outcomes. Differing owner compliance or a more aggressive home therapy protocol may have led to increased joint ROM during gait.

Evidence-based best practice guidelines to enhance stifle kinematics during aquatic or land-based treadmill walking in dogs following stifle stabilisation for CrCL deficiency are lacking. Our study found that the aquatic treadmill improved stifle kinematics as compared to walking on a land-based treadmill, and aquatic treadmill water level was found to further influence stifle kinematics. Stifle ROM increased with increasing aquatic treadmill water level, with peak stifle ROM attained at the hip and stifle water levels. Similarly, peak stifle flexion was the greatest at the hip water level, but peak stifle extension was not affected by water level. Additionally, as water level increased, stance phase percentage decreased. Quantitative kinematic analysis offers a robust means of comparing various conditions used in the rehabilitation process, thereby enabling the development of evidence-based practice guidelines. Despite identification of significantly different stifle joint angles and ROM at different water levels, future studies should investigate whether these differences have a clinically relevant effect on canine mobility and function.

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Conflict of interest

None of the authors of this article has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of the paper.

References

Aragon, C. L. & Budsberg, S. C. (2005) Applications of evidence-based medicine: cranial cruciate ligament injury repair in the dog. *Veterinary Surgery* **34**, 93-98

Arnoczky, S. P. & Marshall, J. L. (1977) The cruciate ligaments of the canine stifle: an anatomical and functional analysis. *American Journal of Veterinary Research* **38**, 1807-1814

Bockstahler, B. A., Größlinger, K., Lendl, S. & Lorinson, D. (2002) The effect of physical therapy on postoperative rehabilitation of dogs after cranial cruciate ligament repair. Proceedings of the Second International Symposium on Rehabilitation and Physical Therapy in Veterinary Medicine. Knoxville, TN, USA, August 10-14, 2002.

Clements, D. N., Owen, M. R., Carmichael, S., *et al.* (2005) Kinematic analysis of the gait of 10 labrador retrievers during treadmill locomotion. *Veterinary Record* **156**, 478-481

Cook, J. L. (2010) Cranial cruciate ligament disease in dogs: biology versus biomechanics. *Veterinary Surgery* **39**, 270-277

DeCamp, C. E., Riggs, C. M., Olivier, N. B., *et al.* (1996) Kinematic evaluation of gait in dogs with cranial cruciate ligament rupture. *American Journal of Veterinary Research* **57**, 120-126

Geigle, P. R., Cheek, W. L., Gould, M. L., *et al.* (1997) Aquatic physical therapy for balance: the interaction of somatosensory and hydrodynamic principles. *Journal of Aquatic Physical Therapy* **5**, 4-10

Gillette, R. L. & Zebas, C. J. (1999) A two-dimensional analysis of limb symmetry in the trot of Labrador retrievers. *Journal of the American Animal Hospital Association* **35**, 515-520

Griffon, D. J. (2010) A review of the pathogenesis of canine cranial cruciate ligament disease as a basis for future preventive strategies. *Veterinary Surgery* **39**, 399-409

Hayes, G. M., Langley-Hobbs, S. J. & Jeffery, N. D. (2010) Risk factors for medial meniscal injury in association with cranial cruciate ligament rupture. *Journal of Small Animal Practice* **51**, 630-634

Holler, P. J., Brazda, V. & Dal-Bianco, B. (2010) Kinematic motion analysis of the joints of the forelimbs and hind limbs of dogs during walking exercise regimens. *American Journal of Veterinary Research* **71**, 734-740

Hottinger, H. A., DeCamp, C. E. & Olivier, N. B. (1996) Noninvasive kinematic analysis of the walk in healthy large-breed dogs. *American Journal of Veterinary Research* **57**, 381-388

Jaegger, G., Marcellin-Little, D. J. & Levine, D. (2002) Reliability of goniometry in Labrador Retrievers. *American Journal of Veterinary Research* **63**, 979-986

Jandi, A. S. & Schulman, A. J. (2007) Incidence of motion loss of the stifle joint in dogs with naturally occurring cranial cruciate ligament rupture surgically treated with tibial plateau leveling osteotomy: longitudinal clinical study of 412 cases. *Veterinary Surgery* **36**, 114-121

Johnson, J. A., Austin, C. & Breur, G. J. (1994) Incidence of canine appendicular musculoskeletal disorders in 16 veterinary teaching hospitals from 1980 through 1989. *Veterinary and Comparative Orthopaedics and Traumatology* **7**, 56-69

Kim, J., Rietdyk, S. & Breur, G. J. (2008) Comparison of two-dimensional and three-dimensional systems for kinematic analysis of the sagittal motion of canine hind limbs during walking. *American Journal of Veterinary Research* **69**, 1116-1122

Lee, J. Y., Kim, G., Kim, J. H., *et al.* (2007) Kinematic gait analysis of the hind limb after tibial plateau levelling osteotomy and cranial tibial wedge osteotomy in ten dogs. *Journal of Veterinary Medicine. A, Physiology, Pathology, Clinical Medicine* **54**, 579-584

Lopez, M. J. (2010) Canine stifle disease: time for a paradigm shift? *Veterinary Surgery* **39**, 269

Marsolais, G. S., McLean, S., Derrick, T., *et al.* (2003) 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

Mendez-Angulo, J. L., Firshman, A. M., Groschen, D. M., *et al.* (2013) Effect of water depth on amount of flexion and extension of joints of the distal aspects of the limbs in healthy horses walking on an underwater treadmill. *American Journal of Veterinary Research* **74**, 557-566

Millis, D. L. & Levine, D. (2014) Aquatic therapy. In: Canine Rehabilitation and Physical Therapy. 2nd edn. Saunders-Elsevier, Philadelphia, PA, USA. pp 536-538

Millis, D. L., Levine, D., Brumlow, M. & Weigel, J. P. (1997) A preliminary study of early physical therapy following surgery for cranial cruciate ligament rupture in dogs. Proceedings of the 24th Annual Conference of the Veterinary Orthopedic Society. Big Sky, USA, March 1-8, 1997.

Monk, M. L., Preston, C. A. & McGowan, C. M. (2006) Effects of early intensive postoperative physiotherapy on limb function after tibial plateau leveling osteotomy in dogs with deficiency of the cranial cruciate ligament. *American Journal of Veterinary Research* **67**, 529-536

Moore, K. W. & Read, R. A. (1995) Cranial cruciate ligament rupture in the dog – a retrospective study comparing surgical techniques. *Australian Veterinary Journal* **72**, 281-285

Ragetly, C. A., Griffon, D. J., Mostafa, A. A., *et al.* (2010) Inverse dynamics analysis of the pelvic limbs in Labrador Retrievers with and without cranial cruciate ligament disease. *Veterinary Surgery* **39**, 513-522

Schwartz, P., Millis, D. L., Hicks, D. A., *et al.* (2004) A kinematic comparison of over ground vs. treadmill walking in dogs. Proceedings of the 31st Annual Conference, Veterinary Orthopedic Society. Big Sky, USA, February 22-27, 2004.

Suomi, R. & Lindauer, S. (1997) Effectiveness of arthritis foundation aquatic program on strength and range of motion in women with arthritis. *Journal of Aging and Physical Activity* **5**, 341-351

Templeton, M. S., Booth, D. L. & O'Kelly, W. D. (1996) Effects of aquatic therapy on joint flexibility and functional ability in subjects with rheumatic disease. *Journal of Orthopaedic & Sports Physical Therapy* **23**, 376-381

Tovin, B. J., Wolf, S. L., Greenfield, B. H., *et al.* (1994) Comparison of the effects of exercise in water and on land on the rehabilitation of patients with intra-articular anterior cruciate ligament reconstructions. *Physical Therapy* **74**, 710-719

Tragauer, V. L. & Levine, D. (2002) Percentage of normal weight bearing during partial immersion at various depths in dogs. Proceedings of the 2nd International Symposium on Rehabilitation and Physical Therapy in Veterinary Medicine. Knoxville, TN, USA, August 10-14, 2002. pp 189-190.

Vasseur, P. B. (1984) Clinical results following nonoperative management for rupture of the cranial cruciate ligament in dogs. *Veterinary Surgery* **13**, 243-246

Wilke, V. L., Conzemius, M. G., Kinghorn, B. P., *et al.* (2006) Inheritance of rupture of the cranial cruciate ligament in Newfoundlands. *Journal of the American Veterinary Medical Association* **228**, 61-64

Witsberger, T. H., Villamil, J. A., Schultz, L. G., *et al.* (2008) Prevalence of and risk factors for hip dysplasia and cranial cruciate ligament deficiency in dogs. *Journal of the American Veterinary Medical Association* **232**, 1818-1824

Supporting Information

The following supporting information is available for this article:

Appendix S1. Pelvic limb kinematics reported for underwater treadmill, over ground and treadmill gait in CrCL-intact and CrCL-deficient dogs