A comparison of stride parameters and carpal and tarsal joint angles during terrestrial and swimming locomotion in domestic dogs

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Abstract
In recent years, canine hydrotherapy has become increasingly popular to treat a range of conditions despite a lack of empirical evidence. It is currently unclear whether joint angles and limb movements performed by dogs during swimming are quantifiably beneficial for healthy animals. This study investigated the swimming kinematics of healthy dogs to establish baseline data for this activity and compare limb kinematics to that of overground locomotion. Kinematic data were recorded from eight healthy dolichocephalic dogs (mean age: 3.4 ± 2.2) of a variety of breeds. Overground data were collected prior to swimming and consisted of dogs trotting on a flat surface. Swimming data were collected using an underwater camera during a standard hydrotherapy session conducted by a trained canine hydrotherapist. Range of motion, primarily due to an increase in flexion, was significantly greater ($p<0.005$) during swimming than trotting. Stride length ($p<0.001$) and frequency ($p<0.005$) were both significantly reduced in swimming compared to trot. Swimming kinematics recorded in this study are consistent with previously published data on canine aquatic locomotion but differ from those previously reported for water treadmill exercise. This study provides an insight into aquatic locomotion in healthy dogs indicating that range of motion exceeds that of terrestrial gaits. It is unclear whether these changes are beneficial for healthy animals and therefore further research is required to develop evidence based protocols for industry practice.

Keywords: Swimming, hydrotherapy, canine, biomechanics,

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Introduction

Hydrotherapy is a form of physiotherapy that utilises the properties of water to treat a variety of conditions (Waining et al., 2011). Human medicine has successfully used hydrotherapy to treat a wide range of neurological and musculoskeletal conditions (Kelly et al., 2000; Marinho-Buzelli et al., 2015; Verhagen et al., 2012). Due to this success, the veterinary profession has begun to utilise similar concepts to aid patients post operatively, as part of a conservative management approach for chronic degenerative conditions or for fitness and training purposes (Dycus et al., 2017; Gaudiano, 2006; Tomlinson, 2012). Despite the increasing popularity of canine hydrotherapy evidence informed practice is currently lacking in this field (Waining et al., 2011).

Two modalities exist for canine hydrotherapy, the pool and the water treadmill (WT) (Winter, 2016). The WT utilises terrestrial gaits, whereas the pool involves swimming for therapeutic benefit (Randall, 2010). Both methods have advantages and disadvantages, however personal preference, availability and practitioner experience are often the determining factors in the choice of modality (Prankel, 2008). Generally the WT provides more control as water depth and speed can be set, however it is more expensive to set up and maintain (Brundell, 2011; Waining et al., 2011). Furthermore, the majority of canine hydrotherapy centres in the United Kingdom only have a pool, hence the facilities available may dictate the type of hydrotherapy that is used, rather than the therapist selecting WT or swimming based on patient requirements (McCormick et al., 2018; Waining et al., 2011).

The properties of water contribute to physiological and biomechanical changes observed during swimming and water treadmill exercise (Barnicoat and Wills, 2016; Nganvongpanit et al., 2011). Buoyancy counteracts the effects of gravity as it is the upward thrust exerted on the body when submerged in a liquid (Molyneux, 2004). The consequent decreased weight bearing is thought to reduce the risk of injury and possibly provide an analgesic effect (Levine et al., 2010; Waining et al., 2011). Water resistance has been reported to increase heart rate and oxygen uptake (Nganvongpanit et al., 2011) and, in combination with viscosity results in individuals expending the same amount of energy as during terrestrial locomotion but at lower speeds (King et al., 2013). Hydrostatic pressure may reduce oedema but can also result in compression of the thorax hence pre-existing respiratory problems are usually considered a contraindication to participation in hydrotherapy (Marsolais et al., 2002; Prankel, 2008).

Although experimental research investigating canine aquatic locomotion is limited, some areas have been explored including the effect of swimming on canine heart rate (Nganvongpanit et al., 2011) and weight loss (Chauvet et al., 2011; Nganvongpanit et al., 2016). Research has also examined the effect of buoyancy jackets (Corum et al., 2014), side effects of a chlorinated pool (Nganvongpanit and Yano, 2012) and physiological effects of water temperature (Nganvongpanit et al., 2014a) on swimming. The effect of swimming on clinical functional parameters and serum biomarkers have also been investigated in both osteoarthritic and healthy dogs (Nganvongpanit et al., 2014b). Marsolais *et al.* (2003) investigated swimming and walking hindlimb kinematics of dogs with surgically repaired cranial cruciate ligaments and identified a greater range of motion (ROM) during swimming for both the stifle and tarsal joints compared to walking. A study of limb coordination during swimming in healthy dogs characterised swimming footfalls as a diagonal sequence pattern and identified trotting as the most similar terrestrial gait (Catavitello et al., 2015). However, a different study suggested that whilst swimming patterns were consistent across breeds, gait patterns in swimming dogs were not characteristic of terrestrial locomotion (Fish et al., 2020). In addition to studying physiological and kinematic variables during swimming, some studies focus on changes post therapy with a single session of hydrotherapy demonstrated to increase the ROM and stride length of both dogs with elbow dysplasia and a healthy control group (Preston and Wills, 2018).

Whilst many studies highlight the ability to increase ROM as a benefit of canine hydrotherapy, evidence is lacking as to whether these increases remain within a physiological spectrum and how they might affect healthy dogs with a normal ROM. Therefore, the aim of this study was to quantify the stride length, stride frequency and ROM of healthy dogs during both overground (trotting) locomotion and swimming.

Materials and Methods

This study received ethical approval from the Hartpury University Ethics Committee on 16.04.18. The study was conducted at Cotswold Dog Spa, Hartpury College and University, Gloucestershire, United Kingdom.

Sample population

A total of nine healthy domestic dogs (*Canis lupus familiaris*) between one and eight years (mean age: 3.4 ± 2.2) of a variety of breeds were initially recruited for the study. Canine participants were dogs owned by University staff and staff members of the Cotswold Dog Spa. Prior to commencement of the study, owners were asked to sign a consent form. Consent forms obtained permission for all aspects of the data collection including the video recording. Owners were also provided with an information sheet containing information about the study.

Inclusion and exclusion criteria

Inclusion criteria stated that all dogs must be over a year of age, clinically healthy, free of water aversion to the owner's knowledge, and have no history of neurological or orthopaedic disease. Brachycephalic and chondrodystrophic breeds were excluded from the study for ethical reasons (Prankel, 2008). Calming signals, such as head turning and nose licking, were monitored throughout the sessions to identify signs of stress or water aversion and allow removal of animals if necessary (Mariti et al., 2017). In accordance with relevant legislation and hydrotherapy regulations, all dogs were referred to the centre by a veterinarian and were assessed by the attending hydrotherapist to ensure they were fit to participate.

Marker placement

Two-dimensional circular reflective markers with a 16mm diameter were cut out from silver duct tape (Kingfisher, London, UK) using a craft punch (Hobbycraft, Christchurch, UK). Markers were placed bilaterally on bony anatomical landmarks while the dog was stood squarely with equal weight distribution through each limb. All markers were placed on the dog by the same investigator and the fur was separated to ensure the markers were in contact with the skin. Sixteen markers, four on each limb, were placed on each dog. The forelimb markers were located between the acromion and the greater tubercle of the humerus, on the olecranon and styloid process of the ulna, and on the distal aspect of the fifth metacarpal bone. The hind limb markers were located on the ischial tuberosity of the pelvis, the stifle joint between the lateral epicondyle of the femur and the fibular head, on the calcaneal tuberosity, and on the distal aspect of the fifth metacarpal bone. For the aquatic locomotion, markerless tracking was used as markers would not remain adhered in the water, this is a similar approach to that used in previous swimming studies (Catavitello et al., 2015).

Overground locomotion

The collection of terrestrial data occurred prior to swimming. This was to eliminate any potential effect swimming may have on overground kinematic parameters (Preston and Wills, 2018). Data were collected on a flat concrete surface. A camcorder (Sony HDR-CX405, Weybridge, UK) with a sampling rate of 60 frames per second (fps) was used for 2D kinematic analysis. The camcorder was mounted on a tripod and a calibration frame placed in the field of view of the camera. The dogs were trotted five times in a straight-line perpendicular to the camera led by their owner. Trot was selected for overground trials as previous research has identified the phase patterns of swimming to be more similar to trot than to walk (Catavitello et al., 2015). The dogs were kept on a loose lead for the duration of data collection (Colborne et al., 2011). Dogs were allowed to locomote at their preferred trotting speed on the basis that dogs were of a range of sizes and that preferred speeds are mechanically similar (Perry et al., 1988). Trials that were subjectively deemed to not be steady state (e.g. involving acceleration or deceleration were removed from analysis).

Aquatic locomotion

Seven of the dogs regularly visited the centre using both the pool and WT, therefore no acclimatisation was deemed necessary. The other two dogs had never visited a hydrotherapy centre before. For these dogs, acclimatisation occurred in the same session as the data collection. The dogs were considered acclimatised once the hydrotherapist deemed them behaviourally settled, following this data collection commenced. One of the two dogs that had not previously undergone hydrotherapy did not acclimatise to the pool and as such was removed from the sample population.

Swimming occurred directly after the overground locomotion session. All dogs swam in a 2x4 metre pool accessed using a ramp. The pool was maintained at a temperature of 30-32^{o}C. The pool had been sanitised with chlorine and had undergone standard checks to ensure pH was at an acceptable level. A calibration object was made from clear plastic attached to a wooden frame and was attached to the pool wall using duct tape. The pool set up consisted of the ramp, a level platform, the calibration object and an action sports camera sampling at 120fps (GoPro Hero 3+, California, US). The camera was placed inside a waterproof housing (GoPro, California, US) and was positioned inside the pool using a jaw flex clip. The camera was located parallel to the calibration object on the opposite side of the pool (Figure 1).

Figure 1. Camera set-up in the hydrotherapy pool

Hydrotherapy sessions were performed as per the standard protocol of the centre and data collection began once the attending hydrotherapist believed the dog was behaviourally settled. All dogs had their collars removed and were fitted with a Ruffwear safety harness (Ruffwear, UK). Dogs were filmed as they swam laps of the pool with rest breaks on the platform. The sessions, including number of laps, were tailored to the individual needs and fitness level of the dog for ethical reasons. Incentives were provided for the dogs and included one or a combination of toys, food and the owner. The hydrotherapist remained close to the dog to ensure they could provide support if required. The hydrotherapist also provided direction, although did not manipulate the dogs while swimming. The swim sessions lasted approximately twenty minutes.

Data analysis

Motion capture software (Dartfish v7.0, Fribourg, Switzerland) was used to analyse both the dry and swimming videos. Swimming strides were only taken from straight line swimming down the length of the pool and did not include turning. Only successfully captured strides were taken forward to data analysis, for the swimming all dogs completed 7.0 valid strides and for the trotting locomotion a mean of 5.9 (+/- 2.03) valid trotting strides were gained per dog. A successful stride was considered the completion of a full gait cycle in the dog’s sagittal plane. From the valid trials that were gained for each dog a mean was calculated for each of the stride parameters. A single gait cycle was considered the period from toe on to the subsequent toe on of the same limb. Due to the lack of ground contact in swimming, an equivalent of toe on was determined where the limb was fully extended beneath the dog (Figure 2). Forelimb and hindlimb stride parameters were calculated individually. The stride parameters measured included stride time (s), stride length (m), and stride frequency (Hz). Maximum and minimum flexion and extension angles (°) and ROM were measured for the carpal and tarsal joints for each stride. The measurement approach for joint angles used in the present study differed from conventional goniometry approaches (e.g. Jaegger et al., (2002)) that are commonly utilised in clinical practice. Measurements reported here were as demonstrated in other kinematic studies (Klinhom et al., 2015).

Figure 2. Position of limb for determination of 'toe on'(left forelimb)

Statistical analysis
Commercially available statistical software (IBM SPSS Statistics v25, Armonk, US) was used to analyse the data. A Shapiro-Wilk test was run to test for normality due to the small sample size. No significant deviation from normality was identified for any of the variables, therefore parametric testing was conducted. The criterion of significance was set at $p<0.05$. Trot and swimming stride parameters were compared using paired t-tests. This included forelimb and hindlimb analysis of stride length, stride time and stride frequency. Carpus and tarsus joint angles were also analysed, including joint ROM, maximum extension and maximum flexion.

Results
Walking and swimming data were collected for eight dogs, with a total of 56 swimming strides and 47 trotting strides taken forward for analysis. Swimming data were not collected for one dog who did not acclimatise to the hydrotherapy pool and was subsequently removed from the study. Stride parameter data are shown in Table 1 and joint angles are shown in Table 2.
Stride length
Forelimb stride length (Figure 3) was significantly longer (t_7=-11.991, $p<0.001$) during trot (1.26m ±0.19) than during swimming (0.61m ±0.12). Hindlimb stride length (Figure 3) was significantly (t_7=-11.997, $p<0.001$) longer during trot (1.30m±0.20) than during swimming (0.64m±0.16).
Stride time
Forelimb stride time was significantly (t_7=5.125, $p<0.005$) longer during swimming (0.71s±0.10) than during trotting (0.47s±0.08). Hindlimb stride time was significantly (t_7=5.737, $p<0.001$) longer during swimming (0.73s±0.11) than during trotting (0.47s±0.07).
Stride frequency
Forelimb stride frequency (t_7=-4.869, $p<0.005$) was significantly higher at trot (2.17Hz±0.36) than during swimming (1.44Hz±0.19). Hindlimb stride frequency was significantly (t_7=-5.136, $p<0.005$) higher at trot (2.17Hz±0.34) than during swimming (1.44Hz±0.24).

Table 1. Mean (±SD) stride parameters for all dogs for swimming and trot. *swimming significantly different to trot.

Condition	Forelimb Stride Length (m)	Hindlimb Stride Length (m)	Forelimb Stride Time (s)	Hindlimb Stride Time (s)	Forelimb Stride Frequency (Hz)	Hindlimb Stride Frequency (Hz)
Swimming	0.61 ±0.12*	0.64±0.16*	0.71±0.10*	0.73±0.11*	1.44±0.19*	1.44Hz±0.24*
Trot	1.26 ±0.19	1.30±0.20	0.47±0.08	0.47±0.07	2.17±0.36	2.17Hz±0.34

Joint ROM

Overall carpal ROM (Figure 3) was significantly increased (t_7=4.892, *p*<0.005) during swimming (136.37°±9.47) compared to trot (115.38°±8.21). Overall tarsal ROM (Figure 3) was significantly increased (t_7=5.474, *p*<0.001) during swimming (90.19°±10.99) compared to trot (59.44°±7.69).

Joint maximum extension

There was no significant difference (t_7=-1.467, *p*=0.184) between carpal maximum extension angle (Figure 3) at trot (181.39°±5.19) and during swimming (176.64°±8.05). The tarsal maximum extension angle (Figure 3) was significantly larger (t_7=-6.140, *p*<0.001) at trot (142.50°±7.25) than during swimming (123.02°±6.09).

Joint maximum flexion

The maximum flexion angle of the carpal joint (Figure 3) was significantly lower (t_7=-8.494, *p*<0.001) during swimming (40.27°±7.88) compared to trot (66.02°±8.45). Tarsal maximum flexion angle (Figure 3) was significantly lower (t_7=-15.032, *p*<0.001) during swimming (32.71°±7.19) compared to trot (83.04°±7.71).

Table 2. Mean (±SD) maximum flexion, extension and overall range of motion of the tarsal and carpal joints of all dogs. *swimming significantly different to trot.

Condition	Carpal Maximum Extension (°)	Carpal Maximum Flexion (°)	Carpal Range of Motion (°)	Tarsal Maximum Extension (°)	Tarsal Maximum Flexion (°)	Tarsal Range of Motion (°)
Swimming	176.64±8.05	40.27±7.88*	136.37±9.47*	123.02±6.09*	32.71±7.19*	90.19±10.99*
Trot	181.39±5.19	66.02±8.45	115.38±8.21	142.50±7.25	83.04±7.71	59.44±7.69

Figure 3. Forelimb and hindlimb stride length (m) and flexion (°), extension (°) and overall range of motion (ROM) (°) of the carpal and tarsal joints. Data shown includes all dogs at swim and trot and is the mean stride length and mean angular data for each dog from all the strides recorded.

Discussion

In this study, significant differences were identified between all swimming and trot stride parameters except for maximum extension of the carpal joint. ROM was significantly increased during swimming with the differences primarily attributed to increased flexion. This is consistent with previous research where increases in hindlimb ROM during swimming have been as a result of increased joint flexion (Marsolais et al., 2003). Stride length (SL) and stride frequency (SF) were both reduced during swimming compared to trot. This differs slightly to WT exercise where whilst stride frequency reduces with increasing water depth, SL is significantly longer in water compared to locomoting on a dry belt (Barnicoat and

Wills, 2016). However, WT studies tend to study walk as opposed to trot so comparisons to the present study may be limited. Trotting on a WT is not commonly performed as part of a therapeutic regimen for dogs or horses, with some suggestion that faster gaits may lack merit on the WT (Tranquille et al., 2017).

Previous research has suggested that buoyancy reduces the mass of the limb that needs to be moved resulting in greater angular velocities and hence ROM during canine swimming (Marsolais et al., 2003). Water temperature potentially improves muscle elasticity and joint extensibility, with the majority of canine hydrotherapy pools kept at a temperature (28 to 30°C) which is comparatively warm compared to equine hydrotherapy (McCormick et al., 2018). If temperature is responsible for the changes in stride parameters seen, any observable benefits may only be short term (Wilcock et al., 2006). It is also possible viscosity and resistance influence the swimming gait. The aquatic medium is reportedly 800 times more viscous than air (King et al., 2013), therefore requiring more effort and energy expenditure to move through (Prankel, 2008; Waining et al., 2011). It has been proposed that during swimming dogs alter their limb sequence timings to generate propulsion hydrodynamically from paddling unlike in terrestrial locomotion where there is contact with a substrate (Fish et al., 2020). This results in a reduced limb extension phase and a longer recovery phase in which the limb is flexed enabling increased thrust and decreased drag during swimming (Fish, 1984).

Although hydrotherapy is frequently used for the management of chronic and degenerative pathologies (Waining et al., 2011), the long term effects of hydrotherapy on ROM remain unknown. Furthermore, it is important to recognise that the substantial changes in ROM associated with swimming could potentially be deleterious for some dogs. Conditions that have been suggested to respond adversely to swimming include acute biceps tendonitis, severe muscle strains and early stages of TPLO or fracture repair recovery (Levine et al., 2004). Therefore, the observed changes in kinematic parameters during swimming may not always be beneficial with negative effects exacerbated in uncoordinated or panicked swimmers. Water is suggested to have analgesic properties (King, 2016), potentially allowing the limb to flex beyond safe parameters. However, conditions frequently referred for canine hydrotherapy such as hip and elbow dysplasia are often characterised by a reduced ROM (Barthélémy et al., 2014; Fries and Remedios, 1995), indicating a benefit to the the use of swimming for these pathologies (Preston and Wills, 2018). In the present study, healthy dogs flexed their limbs significantly more during swimming than trotting. Whilst this might have benefical connotations for performance if an increased ROM is desirable for a particular sport, it is worthy of consideration that these dogs may be experiencing a supraphysiological ROM during swimming.

Stride parameters, including SL, SF and ST, significantly differed between trot and swimming. The results of the present study documented a decreased SL, increased ST, and decreased SF for swimming in comparison to trot. This is consistent with previous research that found the cycle duration of swimming to not be significantly different from walk suggesting that it would be longer than for trot (Catavitello et al., 2015). It is expected that swimming would be slower than comparable terrestrial gaits due to the effect of water resistance (Catavitello et al., 2015). Interestingly, the effect of hydrotherapy on SL differs between the swimming and WT exercise suggesting a benefit to modality selection based on the specific needs of the patient. Equine and canine studies have demonstrated an increase in SL with deeper water depths on the WT when compared with a dry control condition (Barnicoat and Wills, 2016; Scott et al., 2010). SL and SF have also been reported to increase following a single hydrotherapy session in normal and elbow dysplasia dogs (Preston and Wills, 2018). However, these measurements were taken post-session as opposed to during swimming possibly explaining the discrepancy with the findings of the present study. As it has been suggested that dogs utilise a different pattern of limb movements, sometimes referred to as a ‘dog paddle’, during swimming due to the lack of the constraint of a limb contact with the ground (Fish et al., 2020), further research is required to fully elucidate the way both healthy and pathological dogs move in water.

The present study did not include brachycephalic or chondrodystropic breeds partly to standardise the sample population and partly due to known precautions and contraindications to the use of hydrotherapy associated with dogs of these breeds (Prankel, 2008). However, these dogs will often undergo hydrotherapy with extra precautions in place and their differing conformation suggests that they might swim differently to the dolichocephalic breeds studied here. It has been identified that dogs bred for fighting differ in both their anatomy and locomotion compared to breeds bred for running (Alexander, 2002; Pasi and Carrier, 2003) so it can be postulated that they might also utilise different gait patterns during aquatic locomotion. It has been reported that breeds of dog generally swim similarly with varying body mass accounting for differences observed (Fish et al., 2020). However, this study only examined six different breeds none of which were brachcephalic or chondrodystrophic.

Markerless tracking was used in the present study for the swimming condition due to issues with water turbulence displacing markers. Markerless tracking has been used to study canine swimming previously (Catavitello et al., 2015). Markerless tracking has also been validated for canine walking and sit to stand movements (Feeney et al., 2007). Markerless tracking can be considered undesirable due to potential inaccuracy in locating bony anatomical landmarks, however marker based tracking can present similar problems if marker locations are inaccurate (Torres et al., 2010). Soft tissue artefact can hinder accurate identification of bony anatomical landmarks in both markerless and marker based tracking (Gillette and Angle, 2008). This study only utilised 2D kinematic analysis due to the constraints of the aquatic environment, but this approach may have reduced accuracy in the measurement of angular excursions (Miró et al., 2009). However, it has been reported that 2D kinematic analysis provides appropriate accuracy when movements are recorded in the sagittal plane (Feeney et al., 2007). The aquatic environment presents calibration difficulties due to refraction caused by the water, however several studies have reported the accuracy of action sports cameras for underwater use (Bernardina et al., 2017, 2016, 2014). Due to the design of the study, the speeds of both gaits, particularly for swimming, could not be controlled. This potentially introduces inaccuracies into the data, as speed affects most gait parameters (Maes et al., 2008). However, animals have a preferred speed for each gait linked to the smallest possible energy expenditure and dependent on the limb length (Beaszczyk and Dobrzecka, 1989; Hoyt and Taylor, 1981) and this has been suggested to be mechanically similar across individuals (Perry et al., 1988).

In conclusion, the present study has identified some significant differences in the kinematics of healthy dogs during swimming compared to trotting overground. Whilst limb kinematics of dogs and horses on the WT has been studied, swimming remains a comparatively unexplored area. Based on the findings reported here, it is suggested that therapists select hydrotherapy modalities judiciously based on the requirements of the individual and remain aware that the ROM experienced during swimming can exceed that of healthy dogs during overground trotting exercise.

Acknowledgements

We would like to thank the staff of Cotswold Dog Spa for their assistance in conducting this study. We would also like to thank the dog owners who gave up their time and allowed their dogs to participate in this study.

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