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ORIGINAL ARTICLE

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Limbs kinematics of dogs exercising at different water levels on the underwater treadmill

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Abstract

Background: With hydrotherapy rising in the United Kingdom, before understanding the effect of hydrotherapy in animals with pathologies, kinematics data for healthy animals is required.

Objectives: To assess how different water levels on an underwater treadmill (UWTM) can affect joint kinematics.

Methods: Zinc oxide markers were placed on bony landmarks on the limbs of 10 healthy dogs, randomly split into five groups. An UWTM was used with water levels to the digits, tarsus, stifle and hip. The maximum flexion, extension and ROM were determined and a repeated measures ANOVA or Friedman's was used to determine significant differences.

Results: We have detected various changes in kinematics following exercise at different water levels, in comparison with a dry treadmill, including consistent increases in flexion of the elbow, stifle and tarsal joints, which were observed for all water levels. The carpal joint had increases in flexion all water levels apart from digit level. An increase in shoulder flexion was seen only with water on or above stifle level, while hip kinematics had the fewest changes with only ROM increasing at high water level (hip level). Extension of the limbs joints was not markedly affected, with only a few data being significant. The carpal joint had an overall decrease in extension with water at all levels, and the stifle joint had a decreased extension when water was at stifle height.

Conclusions: Water level can significantly affect joint kinematics, and knowledge of how each water level affects the joints is relevant to design tailored hydrotherapy protocols.

KEYWORDS
biomechanics, canine, hydrotherapy, range of motion

1 | INTRODUCTION

Hydrotherapy is a popular modality used to advance rehabilitation and recovery. Underwater treadmills (UWTM), commonly used within canine hydrotherapy, allow the therapist to control speed, water level, incline and temperature, tailoring rehabilitation to individual conditions (Waining et al., 2011). Elucidating the biomechanical requirements of healthy dogs walking on an UWTM is essential to develop treatment plans that are aimed to specific injuries. Some gait parameters have been studied during UWTM locomotion at different water levels, including stride length, stride frequency and duty factor (Barnicoat & Wills, 2016), but there is no studies regarding joints flexion, extension and range of motion (ROM) under different water levels. Range of Motion (ROM) is defined as the degree of motion that occurs when the bones compromising a joint movement about the joint axis (Prydie & Hewitt, 2015). Utilised through assessment and treatment, ROM techniques are used in animal physiotherapy to restore joint range and identify any restrictions and compensatory mechanisms (Zink & Van Dyke, 2013). Improved ROM can be induced by many techniques, manual and remedial, but UWTM effects on all joints ROM are yet to be determined. Current research in human and equine studies have documented an increase in ROM while using an UWTM, however, canine research is still lacking (Barela et al., 2006; Mendez-Angulo et al., 2014). Understanding joint kinematics, including maximum flexion, extension and ROM in the UWTM at different water levels is important for the hydrotherapy industry, as certain conditions present with pain on flexion and/or extension and some conditions present with a deficit of certain movement, which can be restored by hydrotherapy. For example, an increase in carpal flexion could be a significant contraindication for carpal tenosynovitis, and an improved elbow ROM would be sought for elbow dysplasia (Preston & Wills, 2018).

The aim of this study was to determine whether different water levels during UWTM exercise will influence limb joint flexion, extension and ROM when compared with a dry treadmill. It was hypothesised that canine joint kinematics would be characterised by changes in flexion and/or extension in comparison with the dry treadmill.

2 | MATERIALS AND METHODS

2.1 | Animals

Ten healthy dogs (5 males and 5 females) were used in this study. Various breeds were used to represent the full population. As growth plates are seen to close after 1 year, and arthritis commonly occurring at 8–13 years, participants were between the ages of 1 and 7 (mean ± SD = 5 ± 1.9 years old) (Mele, 2007; Todhunter et al., 1997). The withers height was 41.6 ± 12.55 cm and the weight 11.89 ± 9.20 kg. Some dogs were already familiar with UWTM exercise. Participants who were not yet habituated went through habituation periods for three sessions before the main trial.

2.2 | Experimental design

The 10 dogs were randomly split into five groups of two, which were allocated a different randomised sequence of water levels. Upon arrival, each dog was assessed and checked for any signs of lameness. The participants' collar and lead were removed and replaced with a slip lead for the handler in the treadmill to have control in the water. A

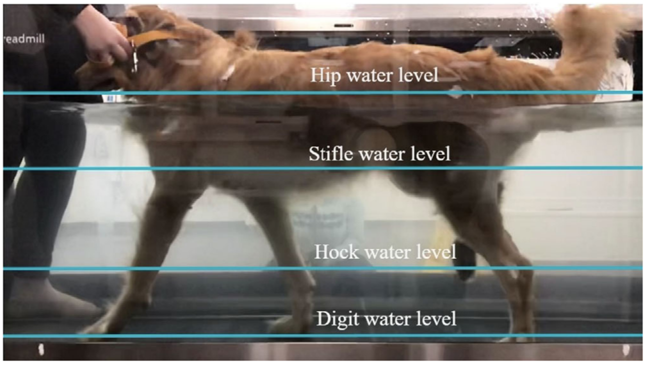

FIGURE 1 Representative image of a dog on the underwater treadmill with lines at approximate water levels used

Canine Hydro-Physio Aqua Treadmill was used for the treadmill exercise. All participants started at the dry condition, so ROM angles were not affected by a carry-over effect of the water levels and results from the dry were used as a baseline for comparisons to be made. Once a gait pattern was noted as being consistent, a 30-s period of gait was recorded. Water height was then progressed randomly through the four water levels for each group; digit, tarsus, stifle and hip level (Figure 1). All participants had 3 min of exercise and 30 s recorded time on each water depth to ensure reliable strides, with at least one to 2 min rest in between each for recovery. Speed was kept constant between water levels and set so that each dog would walk comfortably when the treadmill was dry. Once finished in the trial, dogs were rinsed and shampooed to ensure all chlorine and zinc oxide was removed from their coat. A handler was also present in the treadmill to ensure consistent gait speed and keeping the participants in the sagittal plane. Behaviour and heart rate was monitored throughout the trial.

2.3 | Data collection

Markers were made from zinc oxide ointment similarly to horse participants in the Mendez-Angulo et al. (2013) study. For white coat dogs, the ointment was mixed with powder paint to ensure visibility in the water. On the thoracic limb, markers were placed on the coat over the distolateral aspect of the fifth metacarpal bone, ulnar styloid process, lateral epicondyle of the humerus, greater tubercle of the humerus and dorsal aspect of the scapula. On the pelvic limbs, markers were placed on the distolateral aspect of the fifth metatarsal bone, lateral malleolus of the fibula, lateral femoral condyle, greater trochanter of the femur and the iliac crest (Jarvis et al., 2013) (Figure 2). To ensure consistency, the same researcher and qualified hydrotherapist applied the markers and remained in the UWTM respectively, to control variation.

Two high-speed cameras (Quintic USB3 1.3 MPixels) were positioned on either side of the treadmill, 1 m away from the treadmill, with a field of view capturing the full area of the treadmill window 2 m × 1 m).

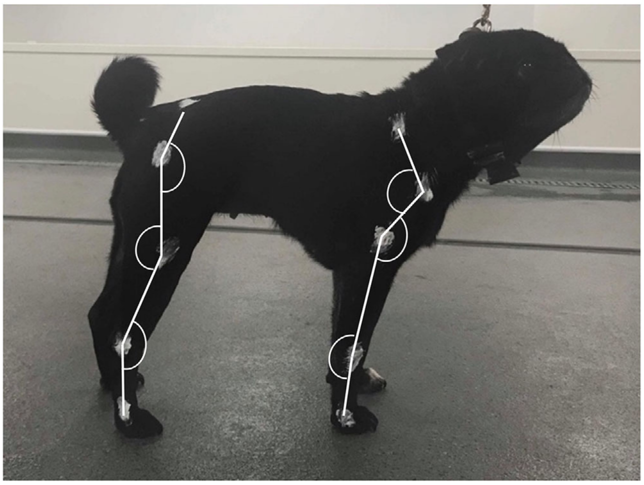

FIGURE 2 Photographic image of a dog indicating the locations of forelimb and hindlimb skin markers (white circles) used to identify body segments (white lines) for determination of joint angles. Measurements of angles for each evaluated joint (shoulder, elbow, carpus, hip, stifle and tarsus) are indicated (curved white lines)

Cameras captured videos at each water level, either side of the UWTM at 240 fps to the 720 p resolution (1280 × 720 pixels).

2.4 | Data analysis

Videos were analysed on video analysis software (Quintic Biomechanics, Quintic Consultancy Ltd, Birmingham, UK). Maximum extension was taken from the maximum angle, the maximum flexion was taken from the minimum angle during a full stride and ROM was calculated by maximum extension minus maximum flexion. Three full strides were analysed for each dog at each water level, in accordance to previously published literature (Marsolais et al., 2003). The selected strides were the ones where the dog was looking forward and gait patterning consistently. Due to the inability to use reflective markers underwater, all video tracking was performed manually. All raw data were smoothed using a Butterworth low-pass filter, fourth order with a cut-off frequency of 10 Hz. Data from three strides were averaged for statistical analysis.

2.5 | Statistical analysis

Mean values of flexion, extension and ROM were placed through statistics software (SPSS Statistics, v. 25). Normality of data was examined through Shapiro–Wilk test. Parametric data was analysed with one-way repeated measures ANOVA, with post hoc tests with Bonferroni correction. Non-parametric data were analysed using Friedman's test, with post hoc applying Bonferroni corrections. For this research, we have just considered the differences between the dry treadmill and the other water heights.

TABLE 1 Forelimb joints flexion, extension and ROM percentage change at all water levels in relation to dry treadmill values ($n = 10$)

Joint Assessed	Water level	Flexion	Extension	ROM
Shoulder	Digit	+1.6%	+0.2%	−1%
	Tarsus	+5.6%	+1.9%	+14.3%
	Stifle	+7.62%	+0.6%	+26.8%
	Hip	+16%	+0.4%	+78%
Elbow	Digit	+13.5%	+0.9%	+23.7%
	Tarsus	+17.62%	+0.7%	+37.3%
	Stifle	+21.1%	+1.8%	+39.2%
	Hip	+27.37%	+6.17%	+97.3%
Carpus	Digit	+7.1%	−3%	+2.2%
	Tarsus	+19.6%	−8.92%	+19.8%
	Stifle	+19.12%	−6.7%	+9.6%
	Hip	+30%	−7.23%	+27.9%

Note: The highlighted numbers represent the water levels where the outcomes were statistically significant different from dry treadmill, in green when there was an increase and in red when there was a decrease ($p < 0.05$).

3 | RESULTS

3.1 | All dogs in the study successfully completed the protocol uneventfully

3.1.1 | Shoulder kinematics

Kinematic analysis revealed that shoulder flexion had statistically significant increases from the baseline dry condition to stifle ($p = 0.023$) and hip level ($p = 0.000015$). Extension did not have a significant difference ($p = 0.147$) between conditions, while shoulder ROM shown significant increase at hip level ($p = 0.047$) when compared with dry treadmill (Figure 2). The percentage on changes in shoulder kinematics in relation to the dry condition can be seen on Table 1 and Figure 3.

3.2 | Elbow kinematics

Kinematic analysis revealed that elbow flexion increases with all water levels in comparison to dry treadmill. A higher joint flexion was achieved at digit level water ($p = 0.007$), tarsus level ($p = 0.000158$), stifle level ($p = 0.001$), with its biggest increase at hip level ($p < 0.0005$). At hip water level, both extension ($p = 0.047$) and ROM ($p < 0.0005$) have increased in relation to the dry condition (Figure 3). The percentage on changes in elbow kinematics can be seen on Table 1.

3.3 | Carpus joint kinematics

Carpal flexion increased at tarsal water level ($p = 0.000132$), stifle level ($p = 0.002$) and hip level ($p = 0.000011$) in comparison with the dry condition. Carpal extension, when compared with the without water

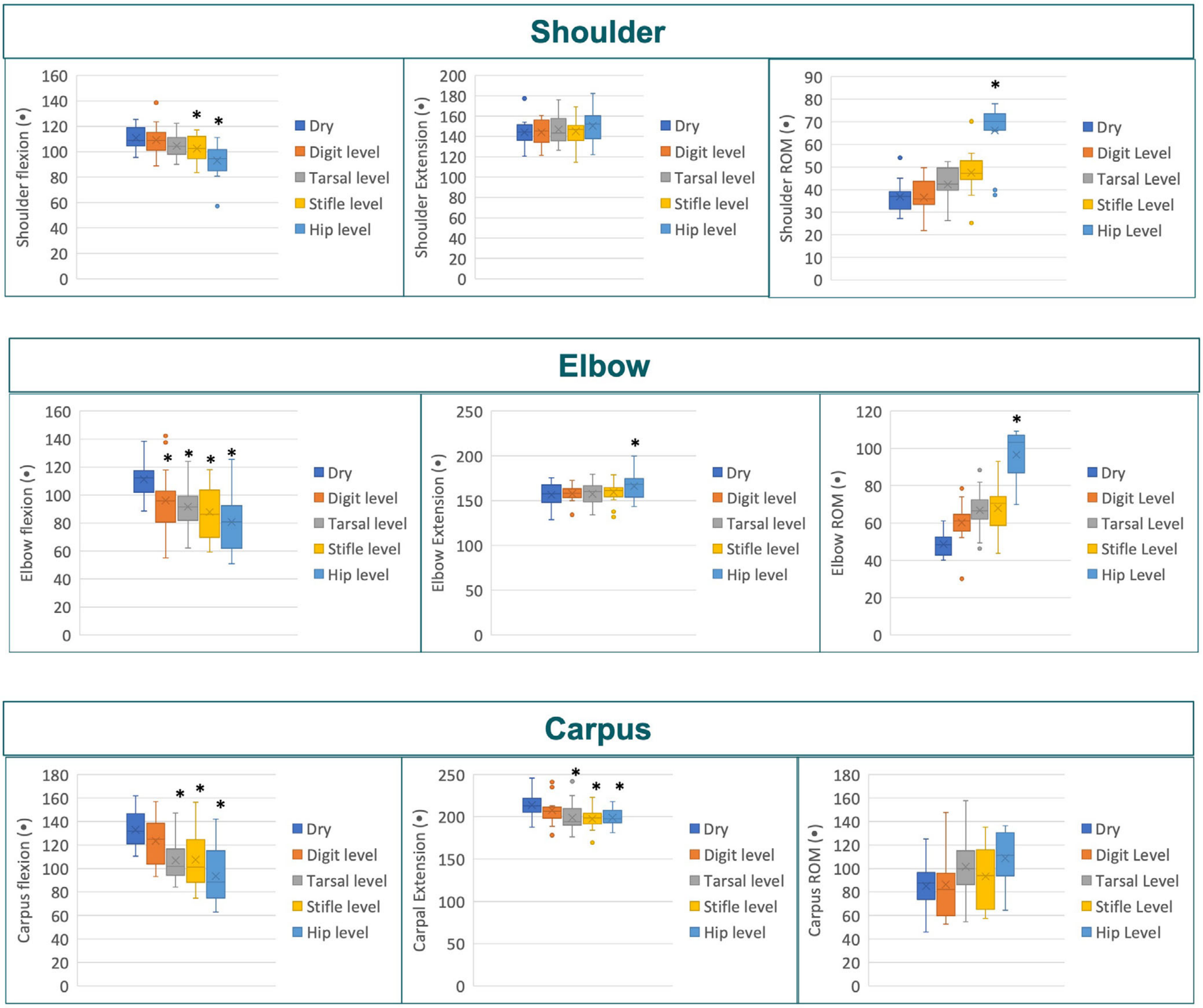

FIGURE 3 Shoulder, elbow and carpus kinematics (flexion, extension and ROM) of dogs ($n = 10$) walking on an underwater treadmill at different water levels (dry, digit, tarsal, stifle and hip level). The bottom and top of the box are the first and third quartiles, the band inside the box is the second quartile (the median), and the '*x*' is the mean. The lines extending vertically from the boxes (whiskers) indicate the minimum and maximum of all of the data. *Significant differences between in relation with the dry condition ($p < 0.05$)

condition, decreased at tarsal level ($p < 0.0005$), stifle level ($p < 0.0005$) and hip level ($p = 0.003$) (Figure 3). Furthermore, due to the increase in flexion and the decrease in extension, there was no elicited changes in ROM. Percentage of changes in carpus kinematics in relation to dry condition can be seen on Table 1.

3.4 | Hip kinematics

There has been no statistically significant differences in hip flexion ($p = 0.005$) or extension ($p = 0.382$) at the different water levels in comparison with without water. However, there was a significant increase in ROM at hip water level ($p = 0.019$) when compared with dry condition (Figure 4). Table 2 shows the changes (in %) of hip kinematics at the different water levels in comparison with dry treadmill.

3.5 | Stifle kinematics

Significant increases in flexion were seen from dry level to digit ($p = 0.004$), tarsus ($p = 0.000005$), stifle ($p < 0.0005$) and to hip ($p = 0.000031$) water levels. Stifle extension was significantly decreased at stifle water level ($p = 0.04$) when compared with dry. Stifle ROM has significantly increased from dry treadmill to the water levels of stifle ($p = 0.007$) and of hip ($p = 0.019$) (Figure 4). On Table 2, these changes can be seen as percentage of change in relation to dry condition.

FIGURE 4 Hip, stifle and tarsus kinematics (flexion, extension and ROM) of dogs ($n = 10$) walking on an underwater treadmill at different water levels (dry, digit, tarsal, stifle and hip level). The bottom and top of the box are the first and third quartiles, the band inside the box is the second quartile (the median) and the '*x*' is the mean. The lines extending vertically from the boxes (whiskers) indicate the minimum and maximum of all of the data. *Significant differences between in relation with the dry condition ($p < 0.05$)

3.6 | Tarsal joint kinematics

When comparing with dry treadmill, analysis has found statistically significant increases in tarsal flexion from dry level to digit ($p = 0.011$), tarsal ($p = 0.000337$), stifle ($p = 0.000001$) and hip ($p = 0.000016$) water levels. However, there has been no significant changes in extension ($p = 0.927$). Tarsal ROM had significant difference at stifle level ($p = 0.004$) and hip level ($p = 0.019$) when compared with the dry condition (Figure 4). These significant differences can be seen on Table 2 as % of change in relation to without water.

4 | DISCUSSION

We have detected various changes in kinematics following exercise at different water levels, in comparison with a dry treadmill. The most marked findings are consistent increases in flexion for the elbow, stifle and tarsal joints, which were observed for all the water levels. The carpal joint had an increase in flexion in most water levels. An increase in shoulder flexion was seen only with water on or above stifle level, and hip kinematics had the fewest changes, with the only significant change being increase in ROM at the highest water level (hip level).

TABLE 2 Hindlib joints flexion, extension and ROM percentage change at all water levels in relation to dry treadmill values ($n = 10$)

Joint assessed	Water level	Flexion	Extension	ROM
Hip	Digit	+5.2%	+0.9%	+20.4%
	Tarsus	+4.2%	+1.5%	+21.1%
	Stifle	+5.4%	+1.9%	+22.2%
	Hip	+23.2%	+3.8%	+44.4%
Stifle	Digit	+10.97%	−3%	+4.4%
	Tarsus	+19.43%	−4.5%	+27.5%
	Stifle	+28.37%	−5.32%	+51.5%
	Hip	+25.1%	+1.8%	+46.6%
Tarsal joint	Digit	+9.18%	−0.1%	+20.5%
	Tarsusl	+15.15%	−5.9%	+46.8%
	Stifle	+21.27%	−6.8%	+62.9%
	Hip	+21.8%	+0.6%	+60.3%

Note: The highlighted numbers represent the water levels where the outcomes were statistically significant different from dry treadmill, in green when there was an increase and in red when there was a decrease ($p < 0.05$).

Extension of studied joints was not markedly affected, with only few outcomes being significantly different from dry treadmill. Carpal joint had an overall decrease in extension during UWTM walking and stifle joint had a decreased extension when water was at the same level as the joint.

To our knowledge, this was the first experiment exploring canine full limb joints kinematics during UWTM exercises. Barnicoat and Wills (2016) have assessed stride parameter changes, but not individual joints kinematics. In Barnicoat and Wills (2016) research there was a significant effect of water depth on duty factor, stride frequency and stride length.

A baseline condition of dry was used to gain comparisons between the different water levels. A 30-s period was filmed in the study as this has been supported in a study by Owen et al. (2004), which found kinematic results to be maintained over a 30-s period in a 2-min test period. Furthermore, Torres et al. (2013) found that ground and treadmill-based walking delivered similar waveforms regarding directional movement. This highlights a similarity between walking on land and walking on the treadmill, which was important in this study to allow comparisons between each water level and the baseline walking on dry.

Immersion to the digit level encourages an increase in elbow, stifle and tarsal flexion (13.5%, 10.97% and 9.18% respectively). Similar observations have been seen in equine research with an increase in elbow, stifle and tarsal flexion; however, carpal flexion was also seen to increase which was not observed in the current study (Mendez-Angulo et al., 2014). This can be attributed to the anatomical and biomechanical differences of the carpal joint in horses and dogs. Dogs have hyperextension of this joint, contributing to an increased extension and ROM.

The results of immersion to the digit level could be an indicator of proprioceptive benefits. Neural pathways are re-established by stimulating nerve signals and motor pathways to activate muscle contraction and stimulate nociceptors (Olby et al., 2005). Peripheral nerve stimulation improves motor performance by stimulating corticospinal pathways, enlarging awareness of the limb (Frank & Roynard, 2018). With a small amount of water touching the limbs, tactile stimulation plays a large role in active ROM. Tactile stimulators act via cutaneous mechanoreceptors, which modulate limb activation in response to cutaneous afferent stimulation (Clayton et al., 2010). The reactive phase of muscular response is the same stimulus triggering flexor or extensor muscles (Rossignol et al., 1981). Research in humans explores cutaneous stimulation of the plantar surface of the foot influencing reflex modulation of the tarsal muscles (Fallon et al., 2005). In the study described here, afferent input from cutaneous mechanoreceptors in the digits region increased tarsal flexion, and consequently the stifle was also stimulated, consistent with the human responses described above. Following this stimulation at digit level, lower joints increase flexion, but no effects were seen at upper joints when the water was only at digit level. In terms of rehabilitation, this study supports water contributing to increased neural input, which will be beneficial for neurological cases that require tactile stimulation to help neural pathways become more efficient.

At tarsal water level, we observed a significant increase in carpal, elbow, stifle and tarsal flexion. Water immersion at the tarsal will provide some resistance and also stimulate cutaneous mechanoreceptors. Muscle activation has been recognised to be in response to cutaneous afferent stimulation (Sherrington, 1910). With the water activating mechanoreceptors for muscle activation, increase in flexion of the carpal, elbow, stifle and tarsal will be activated via the radial and tibial nerve. Furthermore, with the small amount of resistance felt at the tarsal, the participants will increase movement through the joints to overcome the surface tension and resistance by raising the limbs above water level rather than through the water (McGowan & Goff, 2016).

Furthermore, at tarsal level, there is evidence to suggest that buoyancy begins to have an effect as body weight has been seen to reduce by 9%, which reduces vertical ground reaction forces (Levine et al., 2010). The effects of buoyancy may be beneficial for patients with arthritis as it will reduce the weight bearing on the limbs. Accordingly, in our study, carpal extension decreased by as much as 8.92%, which implies less loading of forelimbs during hydrotherapy, as carpal extension is seen to increase when more loading is imposed (Appelgrein et al., 2019). This may be beneficial for some forelimb conditions, which are exacerbated by forelimb loading such as elbow dysplasia. Indeed, description of improvement of elbow ROM following a hydrotherapy session has been described by Preston and Wills (2018).

When the water was raised to the stifle, it began to have an effect on the most proximal joints. All joints, apart from the hip, increased in flexion. Shoulder flexion increased by 7.62%. Reasoning for a difference in shoulder movement at stifle level may be due to the resistance causing the limb to retract more. Furthermore, stifle water level induced the biggest flexion increase at the stifle joint. This reflects Jackson et al. (2002) with joint flexion being its greatest when the water is filled at the joint of interest. Therefore, stifle water level was the first level that encouraged active ROM in the stifle and tarsal joint. It could be suggested that hydrostatic pressure may be acting on the joints by stimulating mechanoreceptors (King et al., 2013).

However, at stifle level, extension of the stifle decreases. This could be due to the cohesion and resistance of the water. Stifle extension occurs in preparation for ground contact at 80% of the total stride (McGowan & Goff, 2016). With depth of immersion, more force is required to move the body against the water resistance (Torres-Ronda & Alcázar, 2014). Therefore, it could be argued that instead of acting against the force, the canine participants exert less force and energy to make it easier when walking through the water, ultimately reducing stifle extension. Therefore, if a dog is presenting with a lack of stifle extension, for example, after cranial cruciate ligament surgery, the UWTM exercise at this level would not bring any benefit in restoring extension as also discussed by Marsolais et al. (2003).

Current research highlights hip water level providing the most reduction in vertical ground reaction forces (Levine et al., 2010). Less concussive forces are placed through the joints at a higher water level and an increase in ROM has been noted in similar research (Mendez-Angulo et al., 2014; Orselli & Duarte, 2011). Hip water level creates the greatest shoulder flexion with a 90.7% increase in ROM. Therefore, if the rehabilitation is targeting shoulder flexion, a higher water level should be recommended.

Elbow flexion increased by 115%, which highlights a reduction in forces being placed through the limbs in order for the elbows to flex. Levine et al. (2010) found 71% of weight distributed to the forelimbs at hip level during stationary partial immersion. However, the study conducted involved walking which encourages individual limb use for correct gait patterning, preventing compensatory mechanisms (Millis & Levine, 2014). During swimming, elbow flexion has been documented to be at its greatest without a floatation device compared to with (Preston et al., 2018).

Stifle flexion decreased at hip water level compared to the stifle water level. This could be due to participants not being able to break water surface tension as the joint was fully submerged (Prankel, 2008). Hip water level did provide the best ROM for the stifle which may be beneficial for conditions that lack overall stifle ROM rather than a reduction in flexion alone which is commonly seen post cruciate surgery (Jandi & Schulman, 2007).

Hip ROM was seen to increase at hip water level by 42%, which could benefit patients with hip dysplasia. Hip water level creates substantial buoyancy (Levine et al., 2010) and Parkinson et al. (2018) found a reduction in activity at the *gluteus medius* so UWTM may not be the ideal modality when an increase in hip extension or flexion is desired.

This study was not without limitations. These factors included the use of a 2-D kinematics analysis and refraction of light in water. However, all attempts were made to minimise these factors: the same researcher placed markers on all, filled the underwater treadmill with water, set up the video camera and manually analysed the videos. In addition, three strides for each dog at each water depth were analysed; this has minimised variability. Some authors, while doing UWTM analysis in horses (Mendez-Angulo et al., 2013), have attempted to correct data for the camera position and refraction of light; however, it is not possible to correct for error attributable to motion of the treadmill, water turbulence, or movement of limbs. As the calculated error due to refraction of light seems to be as low as 1.3% (McCrae et al., 2020), we have conducted without any correction for refraction of water.

In conclusion, the UWTM is a modality that provides therapeutic benefits through the improvement of joint motion, especially joint flexion. The aim of this study was to identify changes in both forelimb and hindlimb kinematics as they relate to a therapeutic programme. The current study has shown that water level has to be adjusted to target specific joint being treated, with higher water necessary to impact kinematics of the most proximal joints. Results have shown that a small amount of water at the digit provides sensory input and could potentially help with inducing a small increase in elbow and stifle flexion. However, it has also shown alternating increases between the stifle and elbow joint at varying water levels due to the different water properties acting on the joints, portraying compensatory mechanisms that occur during UWTM exercise. UWTM exercise has also proved to be safe on the situations where increase in joints extension is not desirable. This piece of research highlights the importance of considering the effects of correct water height when formulating a hydrotherapy protocol.

AUTHOR CONTRIBUTIONS

Jade Terry: supervision (lead); conceptualisation (supporting); investigation (support). Megan Bliss: conceptualisation (lead); writing – original draft (lead); formal analysis (lead); writing – review and editing (equal); methodology (lead); investigation (lead). Roberta Godoy: conceptualisation (supporting); writing – original draft (supporting); writing – review and editing (lead); supervision (supporting); formal analysis (supporting); visualisation (lead).

PATIENT CONSENT STATEMENT

A written informed consent was obtained from the owners of the participants of the study

CONFLICT OF INTEREST

The authors declare they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICAL STATEMENT

The authors confirm that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to and approved by the Animal Welfare Ethics Committee of Writtle University College (protocol 98354474/2018). Although the procedures performed were non-regulated, the guidelines on The Animal (Scientific Procedures) Act 1986 were followed.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1002/vms3.947.

REFERENCES

Appelgrein, C., Glyde, M. R., Hosgood, G., Dempsey, A. R., & Wickham, S. (2019). Kinetic gait analysis of agility dogs entering the A-Frame. *Veterinary and Comparative Orthopaedics and Traumatology*, *32*(2), 97–103. https://doi.org/10.1055/s-0038-1677492 Epub 2019 Jan 31. PMID: 30703813.

Barela, A. M., Stolf, S. F., & Duarte, M. (2006). Biomechanical characteristics of adults walking in shallow water and on land. *Journal of Electromyography and Kinesiology*, *16*(3), 250–256. https://doi.org/10.1016/j.jelekin.2005.06.013

Barnicoat, F., & Wills, A. P. (2016). Effect of water depth on limb kinematics of the domestic dog (*Canis lupus familiaris*) during underwater treadmill exercise. *Comparative Exercise Physiology*, *12*(4), 199–207.

Clayton, H. M., White, A. D., Kaiser, L. J., Nauwelaerts, S., Lavagnino, M., & Stubbs, N. C. (2010). Hindlimb response to tactile stimulation of the pastern and coronet. *Equine Veterinary Journal*, *42*(3), 227–233.

Fallon, J. B., Bent, L. R., McNulty, P. A., & Macefield, V. G. (2005). Evidence for strong synaptic coupling between single tactile afferents from the sole of the foot and motoneurons supplying leg muscles. *Journal of Neurophysiology*, *94*, 3795–3804.

Frank, L. R., & Roynard, P. F. P. (2018). Veterinary neurologic rehabilitation: The rationale for a comprehensive approach. *Topics in Companion Animal Medicine*, *33*(2), 49–57.

Jackson, J., Millis, M., & Stevens, S. (2002). Joint kinematics during underwater treadmill activity. In *Proceeding of the 2nd International Symposium on Rehabilitation and Physical Therapy in Veterinary Medicine* (pp. 189–190). Knoxville, Tenn.

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*(2), 114–121.

Jarvis, S. L., Worley, D. R., Hogy, S. M., Hill, A. E., Haussler, K. K., & Reiser, R. F. (2013). Kinematic and kinetic analysis of dogs during trotting after amputation of a thoracic limb. *American Journal of Veterinary Research*, *74*(9), 1155–1163.

King, M. R., Haussler, K. K., Kawcak, C. E., McIlwraith, C. W., & Reiser, R. F. II. (2013). Effect of underwater treadmill exercise on postural sway in horses with experimentally induced carpal joint osteoarthritis. *American Journal of Veterinary Research*, *74*(7), 971–982.

Levine, D., Marcellin-Little, D. J., Millis, D. L., Tragauer, V., & Osborne, J. A. (2010). Effects of partial immersion in water on vertical ground reaction forces and weight distribution in dogs. *American Journal of Veterinary Research*, *71*(12), 1413–1416.

Marsolais, G. S., McLean, S., Derrick, T., & Conzemius, M. G. (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*, *222*(6), 739–743. https://doi.org/10.2460/javma.2003.222.739

McCrae, P., Bradley-Cronkwright, M., Rolian, C., & Léguillette, R. (2020). Water height modifies forelimb kinematics of horses during water treadmill exercise. *Comparative Exercise Physiology*, *17*, 1–8. https://doi.org/10.3920/CEP200013

McGowan, C., & Goff, L. (2016). *Animal physiotherapy: Assessment, treatment and rehabilitation of animals*. John Wiley & Sons.

Mele, E. (2007). Epidemiology of osteoarthritis. *Veterinary Focus*, *17*(3), 2007.

Mendez-Angulo, J. L., Firshman, A. M., Groschen, D. M., Kieffer, P. J., & Trumble, T. N. (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*(4), 557–566.

Mendez-Angulo, J. L., Firshman, A. M., Groschen, D. M., Kieffer, P. J., & Trumble, T. N. (2014). Impact of walking surface on the range of motion of equine distal limb joints for rehabilitation purposes. *The Veterinary Journal*, *199*(3), 413–418.

Millis, D., & Levine, D. (2014). *Canine rehabilitation and physical therapy*. Elsevier Health Sciences.

Olby, N., Halling, K. B., & Glick, T. R. (2005). Rehabilitation for the neurologic patient. *Veterinary Clinics: Small Animal Practice*, *35*(6), 1389–1409.

Orselli, M. I. V., & Duarte, M. (2011). Joint forces and torques when walking in shallow water. *Journal of Biomechanics*, *44*(6), 1170–1175.

Owen, M. R., Richards, J., Clements, D. N., Drew, S. T., Bennett, D., & Carmichaels, S. (2004). Kinematics of the elbow and stifle joints in greyhounds during treadmill trotting – An investigation of familiarisation. *Veterinary and Comparative Orthopaedics and Traumatology*, *2004*, 141–145.

Parkinson, S., Wills, A. P., Tabor, G., & Williams, J. M. (2018). Effect of water depth on muscle activity of dogs when walking on a water treadmill. *Comparative Exercise Physiology*, *14*(2), 79–89.

Prankel, S. (2008). Hydrotherapy in practice. *In Practice*, *00*(30), 272–277.

Preston, T., & Wills, A. P. (2018). A single hydrotherapy session increases range of motion and stride length in labrador retrievers diagnosed with elbow dysplasia. *The Veterinary Journal*, *234*, 105–110. https://doi.org/10.1016/j.tvjl.2018.02.013 Epub 2018 Feb 24

Prydie, D., & Hewitt, I. (2015). *Practical physiotherapy for small animal practice*. John Wiley & Sons.

Rossignol, S., Julien, C., & Gauthier, L. (1981). Stimulus–response relationships during locomotion. *Canadian Journal of Physiology and Pharmacology*, *59*(7), 667–674.

Sherrington, C. S. (1910). Flexion-reflex of the limb, crossed extension-reflex, and reflex stepping and standing. *Journal of Physiology*, *40*, 28–121.

Todhunter, R. J., Zachos, T. A., Gilbert, R. O., Erb, H. N., Williams, A. J., Burton-Wurster, N., & Lust, G. (1997). Onset of epiphyseal mineralization and growth plate closure in radiographically normal and dysplastic Labrador retrievers. *Journal of the American Veterinary Medical Association*, *210*(10), 1458–1462.

Torres, B. T., Moëns, N. M. M., Al-Nadaf, S., Reynolds, L. R., Fu, Y. -C., & Budsberg, S. C. (2013). Comparison of overground and treadmill-based gaits of dogs. *American Journal of Veterinary Research*, *74*(4), 535–541.

Torres-Ronda, L., & Del Alcázar, X. S. I. (2014). The properties of water and their applications for training. *Journal of Human Kinetics*, *44*(1), 237–248.

Waining, M., Young, I. S., & Williams, S. B. (2011). Evaluation of the status of canine hydrotherapy in the UK. *Veterinary Record*, *168*(15), 407–407.

Zink, M. C., & Van Dyke, J. B. (2013). *Canine sports medicine and rehabilitation*. Wiley-Blackwell.

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