Effect of Water Level on Kinematics of Healthy Horses Walked on an Aquatic Treadmill Compared to Conventional Rehabilitation Techniques

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Abstract

Objectives- To calculate maximal flexion/extension of the carpal, tarsal, and fetlock joints, as well as the stance and swing percentage of the stride in horses walking on the underwater treadmill (UWTM) at four different water levels, and walking on three conventional footings.

Animals- 9 clinically sound adult horses.

Procedures- Two-dimensional data was collected of horses walking on the UWTM at 4 water levels [<1cm of water (Baseline-B), fetlock (F), tarsus (T), and stifle deep (S)], and on hard ground (HD), soft ground (SF), and a land treadmill (LT). Zinc oxide (for UWTM) or retroreflective markers (for conventional surfaces) were used as skin markers and placed at four specific anatomical locations on the left fore and hind limbs. Five gait cycles of each horse for each surface were analyzed. Maximal flexion/extension angles, and range of motion (ROM) were calculated for each joint.

Results-

Underwater treadmill- ROM was greater for all evaluated joints walking in water (F, T, and S) compared to walking in no water (B), mainly due to an increase in flexion. The greatest ROM for each joint was attained at the following water depths (in parentheses): carpus (T), tarsus (S), fore fetlock (F and T), and hind fetlock (F and T).

Conventional surfaces- Maximal flexion of the tarsus and hind fetlock was greater on LT and SF compared to HD, and carpus on LT compared to HD and SF. Maximal extension of the carpus was greater on HD compared to SF and LT, tarsus on HD and SF compared to LT, and both fetlocks on LT compared to HD and SF. The greatest overall ROM of the carpus and fetlocks was achieved on LT, and tarsus on SF.

Conclusions and clinical relevance- These findings suggest that the UWTM is a useful rehabilitation modality for increasing ROM of the distal limbs, and that the depth of water should be considered. Additionally, conventional walking surfaces have a subtle effect on flexion/extension of the distal limb. Therefore, data from this study could help equine clinicians decide which footing surface/water depth is best for each individual orthopedic patient in the early rehabilitation period.

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Introduction and Literature Review

Chapter 1. Introduction and Literature Review

Hydrotherapy

Introduction

Hydrotherapy is defined as the external use of water in the medical treatment of certain diseases. This form of therapy has been used in human rehabilitation for many years,[1,2] and is now gaining popularity in the rehabilitation of small[3] and large animal patients.[4,5] The addition of hydrotherapy in rehabilitation protocols allows for earlier intervention, with patients being able to move within days of injury or surgery with little risk of reinjury. Exercise in water allows patients to unload painful joints or limbs while maintaining soft tissue flexibility and muscle tone.

Swimming was the first form of hydrotherapy used in horses as a method of training and conditioning of healthy animals.[6,7] However, other hydrotherapy methods such as underwater treadmills have recently become available and are currently used in the rehabilitation of equine patients with musculoskeletal injuries. Unfortunately, little scientific information is available regarding the use of hydrotherapy in horses, and equine clinicians and physical therapists are required to design rehabilitation protocols based on data extrapolated from human and small animal studies.

It is important to understand the principles and properties of water (including relative density, buoyancy, viscosity, hydrostatic pressure, and surface tension) to appreciate the benefits of hydrotherapy. These are important components to be considered when designing an aquatic rehabilitation program for equine patients.

Water Properties

Relative density

Relative density depends on the composition of an object, and it is the ratio of the weight of the object to the weight of an equal volume of water.[8] The density of a substance is defined by a pure number value called specific gravity. The specific gravity of water is 1.0,[9] and the relative density and specific gravity of an object determine if the object floats or sinks in water.[10] Objects with specific gravities greater than 1 tend to sink; however, if the ratio is less than 1, the object tends to float. The specific gravities of fat, lean muscle, and bone are 0.8, 1.0, and 1.5-2.0, respectively.[9] Therefore, if the specific gravity of a lean animal is greater than 1, the animal will tend to sink; whereas if the specific gravity of an obese animal is less than 1, the animal will tend to float. The greater the specific gravity of an object, the faster the sinking velocity.[9]

Buoyancy

Any body submerged in water is subjected to two forces, gravity and buoyancy. Buoyancy is defined as the upward force exerted by a liquid, gas or other fluid, that opposes an object's weight.[9] Archimedes' principle states that an object that is fully or partially submerged in a fluid experiences an upward thrust equal to the weight of the fluid displaced.[8-10] An immersed limb or body with a relative density less than 1 (water's density) will be lifted toward the surface by buoyant forces.[11] Thus, an animal with a relative density less than 1 floats because of the water displaced.[9] Buoyancy is exerted directly through the center of buoyancy, which is the center of the displaced volume of water and depends on the distribution of the displaced volume of fluid relative to an object.[9] The center of gravity and the center of buoyancy have to be in the same vertical line to maintain stability. If this is not the case, an animal will tilt in order to reach a state of equilibrium.[9]

Buoyancy assists in the rehabilitation of orthopedic patients by taking some of the weight off of weak limbs or painful joints. It allows the patient to exercise in an upright position and may decrease pain by minimizing the amount of weight bearing. For example, the effect of buoyancy has been evaluated in horses, resulting in a reduction of 10% in body weight when water (saline) was at the level of the olecranon, and 75% when water (saline) was at the level of the tuber coxae.[12] At lower water levels, the effect of buoyancy has not been measured in horses, but a similar canine study[13] showed that vertical ground reaction force only decreased by 9% after immersion to the tarsal joints, and by 15% after immersion to the stifle joints. In humans, the percentage of the weight borne when immersed in water is approximately 40% to 56% at the level of the anterior superior iliac spine, 25% to 37% at the level of the xiphoid, and 5.9% to 10% at the seventh cervical vertebra.[14,15] This data is particularly useful when treating patients with chronic conditions such as arthritis because joints may be unloaded during exercise.

Hydrostatic Pressure

The fluid pressure exerted on a body is equal on all surfaces of an immersed object and is directly proportional to both the density of the fluid and the depth of the fluid.[10] The atmospheric pressure at the surface of water is 1.00 kPa and pressure increases by 0.029 kPa per foot of depth.[9] Thus, the deeper a body is immersed the greater the pressure exerted. This principle has several advantages in rehabilitation. First, hydrostatic pressure provides constant pressure to a body or limb immersed in water which helps provide stability for weak animals while in the standing position. Second, hydrostatic pressure opposes the tendency of blood and edema to pool in the lower portions of the body and can therefore aid in reducing swelling and edema.[11] Finally, hydrostatic pressure may also decrease pain during exercise. By providing phasic stimuli to the skin sensory receptor, the water's motion decreases nociceptor hypersensitivity, allowing the patient to perform a variety of movements with less pain.[16]

Viscosity

Viscosity is a measure of the resistance of a fluid which is being deformed by either shear or tensile stress. Viscosity is significantly greater in water than in air,[11] making it harder to move through water than through air. Therefore, exercise in water provides resistance that may strengthen equine muscles and improve cardiovascular fitness. Additionally, viscosity increases sensory awareness and supports unstable limbs or joints.[11] Water resistance is also influenced by the movement of water. For instance, a streamlined water flow offers less resistance to movement than does a turbulent flow.[8] Additionally, resistance in aquatic exercise may be increased by increasing the velocity of movement of the patient or increasing the surface area of the body part moving in water.[17]

Surface tension

Surface tension is a property of the surface of a liquid or fluid that allows it to resist an external force.[9] This is due to the tendency of water molecules to adhere together on the surface, causing a slightly greater resistance to movement on the surface of water compared to deeper levels.[9] Surface tension is not a factor when a body is completely submerged in water, but it becomes an important factor when a limb breaks the surface of the water. Therefore, this water property can be used to increase the intensity of an aquatic rehabilitation exercise.

Swimming pools and underwater treadmills for horses

Swimming Pools

Equine pools were initially designed for training and conditioning of race horses, but they are now also used for rehabilitation of certain musculoskeletal conditions. The shape and size of the pool varies depending on the intended use. Some pools are round; some are straight with a ramp for entry and exit at each end; and some are a combination of both designs. The advantage of straight pools is that if the horse becomes distressed or exhausted during swimming it can leave the pool easily. This is an important factor because swimming is an anaerobic exercise where horses reach heart rates up to 200 beats per minute,[6] and can cause a significant increase in blood pressure.[18] Therefore untrained animals can get tired very quickly, and exhaustion of the horse should always be avoided because aspiration of water can be fatal.

The major benefit of swimming is the fact that horses can exercise intensively without bearing any weight in limbs and joints. Therefore, this modality is considered ideal to improve cardiovascular fitness of race horses while avoiding loading of bones and joints.

Underwater treadmills (UWTM)

In human rehabilitation, underwater treadmills are often used as an alternative to swimming and are thought to be particularly beneficial for injuries of the limbs.[19] Many equine training centers and veterinary hospitals have underwater treadmills available to provide an alternative to swimming for equine patients. This rehabilitation modality presumably provides some of the benefits of hydrotherapy, such as reducing the concussive forces experienced by the distal limb, while providing controlled aerobic exercise.[20] Underwater treadmill exercise is considered to be a form of aerobic exercise where horses reach heart rates up to 78 beats/minute at the walk[21] and 120 at the trot.[5] With water immersion, there is a decrease in systemic vascular resistance, and the changes in total peripheral resistance are dependent on water temperature.[18] After underwater treadmill exercise there is a moderate but non-significant increase in blood lactate and plasma creatine phosphokinase levels.[22] In addition, it also provides a different type of muscle exercise compared to swimming because the limbs are partially loaded.[13] Resistance to joint movement is also a benefit by increasing the muscle contraction required to move the limb without having excessive force placed on the bone or joint surface. The use of an underwater treadmill allows maintenance of cardiovascular fitness, muscle tone, and improved joint movement without undue stresses occurring on the injured limb.[23] The reason for the decreased stress placed on the limb is the buoyancy that the water provides. A certain amount of this depends on the amount of water in relation to the body mass of the horse.[12] Therefore the partial loading the limb combined with the benefits of hydrotherapy may allow for use of different groups of muscles than when working on land or in swimming pools.[23]

Evidence of the benefits of hydrotherapy in humans and small animals

The benefits of exercising in water have been reported in humans and small animals, but information is scarce in horses. Several human and canine publications have demonstrated that hydrotherapy is beneficial for pain, limb function, joint mobility, muscle strength and balance.[1,2,24]

In human medicine, hydrotherapy is extensively used in the rehabilitation of orthopedic patients after injury or surgery, and for the management of chronic conditions such as osteoarthritis. For instance, progressive aquatic resistance training has favorable effects in patients with decreased mobility, lower limb muscle power, and muscle cross-sectional area in patients after knee replacement.[25] Physical therapists also use hydrotherapy in the rehabilitation period after shoulder surgery because movement of the shoulder in the water requires less muscle activation than on land,[1] due to the effect of buoyancy, which allows earlier intervention with less stress on the affected soft tissues. A recent study showed that aquatic therapy significantly improved passive flexion range of motion of the shoulder in patients with surgical rotator cuff repair at three weeks after surgery.[26] Water exercise was more effective in reducing joint effusion and returning limb function after cruciate ligament reconstruction than exercise on land.[27] In patients with osteoarthritis, exercise in water has been shown to decrease pain and improve limb function while increasing muscle strength and joint range of motion.[28] Other studies showed that outcomes following aquatic exercise for adults with arthritis were comparable to land based exercise, and concluded that aquatic exercise provides an alternative strategy for patients that find land based exercise difficult.[28,29] Aquatic therapy is also a viable option for patients with obesity who have difficulties with active exercise on land due to knee osteoarthritis.[30] Patients with rheumatoid arthritis also experienced an improved emotional and psychological state, along with improved joint range of motion and reduced pain after aquatic exercise.[24]

Currently, there are only a few studies investigating the advantages and benefits of hydrotherapy in small animal rehabilitation, although it is widely used in clinical practice.[23] Most of the hydrotherapy protocols used to date in the canine patients have been extrapolated from human studies, and mainly consist of swimming or walking in water. Swimming is often added to the rehabilitation program for the canine patient following surgery for cranial cruciate ligament deficiency as it results in greater ROM of the stifle and tarsal joints than does walking on land.[31] A force plate study showed that active exercise and swimming improved limb function after cruciate repair with no measurable difference between the affected and unaffected limbs at 6 months after surgery.[32] Similarly, after tibial plateau leveling osteotomy, dogs showed improvement in limb function when early intensive postoperative physical therapy included passive ROM and training on an underwater treadmill (UWTM).[33] Therefore, underwater treadmill therapy has become popular for the rehabilitation of canine orthopedic injuries because of its beneficial effects on joint range of motion. Joint kinematics of dogs have been studied while walking on an underwater treadmill and compared to those of walking on land. Researchers showed that joint flexion was greater walking in water than on land, and that joint flexion was the greatest when water was filled higher than the joint of interest. Additionally, joint extension was also achieved with underwater treadmill walking, which is not the case in swimming.[34]

Claimed benefits of hydrotherapy in horses

Based on scientific research from human and small animal rehabilitation, the claimed benefits of hydrotherapy in horses include the followings:

- Reduces loading of weak or painful joints
- Provides additional support to a body or limbs
- Allows earlier intervention after injury or surgery
- Prevents muscle atrophy and soft tissue adaptive shortening
- Increases muscle mass and strength
- Promotes cardiovascular fitness and endurance
- Increases soft tissue flexibility
- Decreases edema and joint effusion
- Increases circulation and stimulates healing
- Allows gradual progression and return toward normal limb function
- Decreases pain
- Encourages joint range of motion

Range of Motion

Introduction

Range of motion (ROM) of a joint is defined as the full possible movement of a joint, from maximal extension to maximal flexion. ROM of each joint is influenced by the structure, integrity, volume, and the surrounding soft tissues of the joint such as tendons, ligaments, and muscles.[35] In mammals, there are three types of joints: synarthroses, amphiarthroses, and diarthrodial joints. Of these, diarthrodial joints have, by far, the greatest ROM of all joints, and exhibit characteristic movements depending on the joint. For instance, the metacarpophalangeal joint (fetlock in the horse) exhibits mainly flexion and extension; however, the hip joint exhibits flexion, extension, abduction, and adduction.

In orthopedic patients, preservation of joint movement is crucial after surgery in order to avoid stiffness of the soft tissues and thus loss of limb function. ROM exercises are particularly useful to diminish the effect of disuse and immobilization of limbs.[36] Similarly, ROM and stretching exercises are very important in chronic conditions to reestablish flexibility of the soft tissues and regain or at least maintain mobility. Joint movement may be passive, active-assisted, or active.

Passive range of motion

Passive ROM is the movement of a joint that is performed without muscle contraction within the available ROM, using an external force. If additional pressure is applied at the end of the available ROM, it is termed stretching. In veterinary medicine, both passive ROM and stretching are performed by clinicians or physical therapists.[37]

The ROM of a joint can be limited by either physiologic or pathologic conditions that may involve the joint capsule, periarticular soft tissues, ligaments, tendons, muscles, or skin. For example, a large open wound over a joint that is allowed to heal by second intention may result in thick scar tissue that limits the joint ROM.[37] Additionally, pathologic changes in the cartilage, synovial fluid, or synovium of a joint can cause a marked reduction in ROM. An example of chronic condition affecting ROM in humans and horses is osteoarthritis.[38-40]

The most common indication for passive ROM exercises is immediately after surgery, before active weight bearing of the affected limb starts, to help prevent joint contracture and adaptive shortening of soft tissues, and to reduce pain, enhance blood and lymphatic drainage, and improve synovial fluid production and diffusion.[36] Another indication for passive ROM is the prevention of joint contracture during the healing period in paralyzed patients, or after a prolonged period of immobilization (e.g. fractured limbs treated with a cast). However, in these cases passive ROM will not prevent muscle atrophy, or improve strength and endurance of the muscle groups.[37]

Passive ROM should always be performed when the patient is relaxed and comfortable. The administration of analgesics and/or non-steroidal antiinflammatories is recommended before ROM exercises to reduce pain. The exercise should not cause any pain or discomfort, and a gentle technique is mandatory to avoid undesirable reactions. The therapist should grasp the proximal and distal aspect of the limb avoiding painful areas. The motion should be smooth, slow, and steady to make sure that the patient can tolerate it.[37]

Active-assisted range of motion

Active-assisted range of motion is a combination of patient´s muscle activity and passive motion provided by the therapist.[37] In veterinary medicine, this type of ROM is more commonly performed than passive ROM because it is difficult to avoid muscle activation in patients.[37] Active-assisted ROM is an ideal exercise for weak patients, especially for those recovering from a fracture treated with immobilization. In these cases, active assisted ROM allows muscle strengthening while the soft tissues of the affected limb recover flexibility.[20]

In small animals, active assisted ROM exercises can be performed with the help of a sling to support the patient during ambulation.[37] Swimming and walking in an underwater treadmill are other forms of active assisted ROM that can be used in both small and large animals.[31,41] The water provides buoyancy to help support the weight of limbs while the limbs go through a cycle of motion.[13]

Active range of motion

Active ROM is the motion of a joint that is achieved by muscle contraction. This motion may be attained during a regular gait cycle (e.g. walking) or under special conditions designed to maximize joint motion and to use the full available ROM. In equine rehabilitation, some examples of these exercises include walking over poles or cavalletis, or the attachment of tactile stimulator and/or weights.[42]

As the patient improves flexion and extension of a joint, it is helpful to continue to perform passive or active assisted ROM to achieve as complete ROM as possible, and then perform active ROM to emphasize more complete use of the limb.[20] Active ROM requires more muscle activity and, when used in combination with stretching exercises, allows patients to recover maximal flexibility and strength of the affected soft tissues.[37]

Kinematic analysis

Introduction

In horses and small animals, kinematic analysis is commonly used in research studies to evaluate the effect of different rehabilitation techniques and exercises on limb movement and joint motion. Kinematic analysis measures the geometry of movement without considering the forces that cause the movement.[43]

Kinematic analysis objectively quantifies the features of the equine gait that are assessed subjectively during a lameness examination. The results are expressed in the form of temporal (timing), linear (distance) and angular measurements that describe the movements of the body segments and joint angles. Today, the most popular techniques for studying kinematics and joint motion in horses are videographic analysis, optoelectronic systems, and electrogoniometry.[43]

In equine research, sound horses are often used because their kinematics are stable and symmetric, and analysis of a relatively small number of strides is representative of the gait pattern. Some authors have suggested that 3–5 strides are sufficient for kinematic analysis.[44] The data describing an equal number of strides for each limb are averaged and considered to be 'representative' for that particular limb.

Videographic systems

Videography is a well-accepted method of kinematic analysis for research and lameness evaluation in horses. It involves attachment of several markers to the horse, setting up and calibrating the equipment, video recording, and digitization, transformation, smoothing and normalization of the data. Kinematic analysis may be performed in two or three dimensions.[45] Since the limbs of the horse move primarily in the sagittal plane, most of the useful information is captured by the two dimensional system, and in many studies the extra effort involved in extracting three dimensional data is unnecessary. However, three dimensional analyses are mandatory when a study involves evaluation of the abduction/adduction or internal/external rotations of the limb.[43]

Kinematic data provides temporal, linear and angular variables during motion.[43] Temporal data describe the stride duration, and is calculated from the frame numbers and the sampling frequency. Distance data is computed from the coordinates of the markers combined with the calibration information, and describe the stride length, distance between limb placements, and the flight arcs of the limbs. Angular data describe the velocities, accelerations, and displacements of the body segments and joints. In two dimensional studies, the angular data are usually reported as flexion and extension in the sagittal plane.[43] For this purpose, the centers of rotation of the appendicular joints have been described,[46] and these locations are often used as landmarks for placement of skin markers. In three dimensional analysis, standardization becomes much more complicated. However, this system allows the true measurement of three types of joint motion; flexion/extension, adduction/abduction, and internal/external rotation.[43] Speed is an important fact that affects equine kinematics substantially, and therefore studies performed at different speeds are not comparable.[47]

Most video systems offer automated digitization of skin markers if they have been placed correctly and if lighting is appropriate. For two dimensional systems, 2-3 cm diameter circular retroreflectivemarkers are commonly used.[48] Self-adhesive tape or cyanoacrylate glue is effective for securing the markers. For three dimensional studies, spherical markers are used because cameras can capture them when viewed from different angles.[43] Marker locations are chosen in accordance with the purposes of the analysis. Calculation of the angle between two limb segments in two dimensions requires a minimum of three markers. Some software allows the use of two markers per segment that are aligned along the long axis of the segment, without necessarily being placed over the joint centers.[45] Skin movement relative to specific underlying bony landmarks is a source of imprecision, and it has been quantified in Warmblood horses.[49,50] Additionally, correction algorithms have been developed for walking and trotting; however, they are only valid for horses of similar conformation and moving at the same gait and speed. Skin movement artifact distal to the elbow of the forelimb and the stifle of the hindlimb, is small enough to be ignored. However, in the more proximal parts of the limb skin movements are sufficient to change the measurement of the angles of proximal joints.

Joint angles are typically measured on the anatomical flexor aspect of the joint, and reported as the flexion and extension angles relative to the rotation of the proximal and distal segments. Although the patterns are the same regardless of the method of measurement (2-D versus 3-D systems), the values differ considerably, which impairs comparisons between data from different studies.

Optoelectronic systems

Data collection and processing using an optoelectronic system is similar to those used for videographic systems. Several optoelectronic systems are available, and use either active markers (that emit a signal) or passive markers (that detect a signal).[43] Use of these systems is usually confined to the laboratory, because of the need for a hard-wired connection to the subject and/or controlled lighting conditions. These systems perform the digitizing on-line, so data are usually available very quickly.[43] Many of the systems have a built-in method for distinguishing between individual markers, for example by sequencing the temporal output of different markers or by using markers of different shapes or colors.[43] In equine research, optoelectronic systems have been used to evaluate joint kinematics at different gait patterns in normal and lame horses,[51,52] and to assess kinematics of trotters at different speeds.[53]

Electrogoniometry

An electrogoniometer is a device for measuring joint angle changes. It consists of a potentiometer affixed to two rotating metal arms. These metal arms are usually attached to the equine limb with tape, so that the center of rotation lies over the center of a joint (e.g. fetlock joint).[43] During movement, joint angle changes alter the electrical resistance of the potentiometer, which is calibrated to produce a proportional displacement of known magnitude.[43] In equine research, electrogoniometry has been used to evaluate joint movements at different gait patterns in normal and lame horses,[54] and to assess the changes in joint motion after medical or surgical treatments.[55]

Measurement of the flexion/extension angles of the equine distal limb joints

Recently, the passive range of motion of the equine distal limb joints have been measured by goniometry in standing and anesthetized healthy horses.[56] This technique was also used in a study that evaluated the effect of 8 week duration casting on the range of motion of the forelimb fetlock joint.[57] However, measurement of active joint ROM angles requires the use of a kinematic analysis system (i.e. videographic analysis, optoelectronic system, or electrogoniometry).[58]

Kinematic studies have been performed to characterize the changes in flexion and extension of the distal limb joints at different gait patterns in normal and lame horses,[52,59-61] to evaluate the effect of different rehabilitation techniques,[42,62] and to compare results of medical and surgical treatments.[63] Other researchers have also measured joint ROM of distal limb joints (i.e. fetlock) to compare the effect of different footing surfaces.[64] However, to the author's knowledge, the effect of conventional walking surfaces on the flexion and extension of healthy horses have not been compared so far, and comparison between the published studies is difficult because the variability in methodology (e.g. kinematic analysis systems, settings, placement of skin markers, speeds, etc.).

Additionally, the effect of water level in the kinematics of horses walking in an underwater treadmill is currently unknown, which make it difficult for clinicians and physical therapists to recommend a water level when designing a rehabilitation program. In Table 1, we have summarized the maximal flexion and extension angles of the carpus, tarsus, and both fetlocks (i.e. fore and hind) that have been reported using similar methodology to our study.[59,60]

Table 1. Maximal flexion (Flex) and extension (Ext) angles of the carpus, tarsus, fore fetlock, and hind fetlock of healthy horses recorded using a videographic system at the walk reported 2000 and 2001 by Hodson et al.[59,60] Angles are expressed in degrees.

Carpus		Tarsus		Fore Fetlock		Hind Fetlock	
Flex	Ext	Flex	Ext	Flex	Ext	Flex	Ext
125.2	181.8	125.2	167.6	165.4	219.9	151.1	214.6

Chapter 2

Effect of water level on flexion and extension of the distal limb joints of healthy horses walked on an underwater treadmill

Chapter 2. Effect of water level on flexion and extension of the distal limb joints of healthy horses walked on an underwater treadmill

Chapter Summary

Objective- To calculate maximal flexion and extension of the carpal, tarsal, and fetlock (fore and hind) joints, as well as the stance and swing percentage of the stride in horses walking on an underwater treadmill (UWTM) at four different water levels.

Animals- 9 sound adult horses.

Procedures- Data of horses walking (0.9 m/s) on the UWTM at 4 different water levels [<1 cm of water (baseline-B), fetlock (F), tarsus (T), and stifle deep (S)] were recorded by one video camera and analyzed using 2-dimensional motion-analysis software. Zinc oxide was used as skin markers at four anatomical locations on the left fore and hind limbs. Maximal flexion and extension angles, and range of motion (ROM) were calculated for each joint, and the percent of the stride in stance or swing phase was calculated for each stride.

Results- ROM was greater for all evaluated joints walking in water (F, T, and S) compared to walking in no water (B), mainly due to an increase in flexion. The greatest ROM for each joint was attained at the following water depths (in parentheses): carpus (T), tarsus (S), fore fetlock (F and T), and hind fetlock (F and T). As the water level increased the stance percentage of the stride decreased and swing percentage increased.

Conclusions and clinical relevance- These findings suggest that the UWTM is a useful rehabilitation modality for increasing the ROM of various joints, and that the depth of the water in the UWTM should be considered depending on the specific joint or limb being targeted.

Introduction

Hydrotherapy is a well-established rehabilitation therapy in human medicine [25,27-29] and is gaining popularity in small animal patients [3,65] and horses.[4,41,66] The physical properties of water such as buoyancy, viscosity, resistance, hydrostatic pressure, and surface tension offer specific benefits that should be considered when designing a rehabilitation program.[10] Water can decrease the amount of weight placed on joints, provide constant pressure to a body or limb submerged in water, and aid in venous and lymphatic drainage. Exercise in water may also decrease pain perception by providing a phasic stimulus to the sensory receptors, and help strengthen muscles and promote cardiovascular fitness.[5,6,13,67] In humans and small animals, these advantages have been suggested to allow orthopedic patients earlier use and weight bearing on weak limbs or painful joints after injury or surgery, while minimizing the risk of re-injury.[2,32,68]

Underwater exercise (such as swimming) has been a common conditioning method for non-injured equine athletes for years,[7] but more recently it has also been used as a rehabilitation method for recovery from some musculoskeletal injuries.[23] However, swimming is considered a high intensity activity in horses, where heart rates higher than 200 beats/minute may be reached,[6] which is not ideal for equine orthopedic patients immediately after injury, surgery, or a period of prolonged rest. In human medicine, underwater treadmills (UWTM) are often used as an alternative to swimming and is thought to be particularly beneficial for injuries of the limbs.[19] Many equine training centers and veterinary hospitals have underwater treadmills available to provide an alternative to swimming for equine patients. This rehabilitation modality presumably provides some of the benefits of hydrotherapy, such as reducing the concussive forces experienced by the distal limb, while controlling aerobic exercise in the early rehabilitation period with heart rates up to 78 beats/minute at the walk[21] and 120 at the trot.[5]

The ultimate goal of any musculoskeletal rehabilitation program is to restore limb function through maximizing flexibility of the injured soft tissue, recovering muscle and bone strength, and re-establishing full range of motion (ROM) of affected joints.[20] In human medicine, there is evidence that early passive and/or active flexion and extension of injured appendages is crucial in order to obtain the best outcome.[25,69] This improvement in limb function and ROM has also been demonstrated in post-operative human and canine studies using hydrotherapy.[25,26,31,33] However, to the authors' knowledge, there have been no similar reports of the use of hydrotherapy and its affect on ROM of distal limb joints in horses. Determination of whether an UWTM increases ROM in the distal limb joints of horses, and which water level is most beneficial to each area of the limb, will benefit clinicians and physical therapists when designing a rehabilitation program.

Therefore, the objectives of this study were to: 1) calculate the maximal flexion and extension angles, and the ROM of the carpal, tarsal, fore fetlock (metacarpophalangeal), and hind fetlock (metatarsophalangeal) joints in four different water levels: < 1 cm of water (baseline-B), water up to the hind fetlocks (F), tarsi (T), and stifles (S); 2) calculate the percent of the stride spent in stance or swing phase; and 3) determine which of the four water levels provides the greatest flexion and extension for each joint. We hypothesized that ROM of the distal limb joints would increase when horses are walked in an UWTM with any water level (F, T, and S) compared to walking with no water (B). Additionally, we hypothesized that joint flexion and extension, as well as the percent of the stride spent in the swing phase would increase with increasing water depth.

Material and Methods

Horses - Nine clinically sound horses (8 Quarter Horses and 1 Thoroughbred) were used in the study. Mean ± SD age of the horses was 8.1 ± 4.3 years; mean weight was 486.6 ± 26.3 kg; and mean height at the withers was 150.1 ± 3.2 cm. Before horses were enrolled in this study, a thorough physical examination and subjective lameness evaluation were performed on each horse. No clinical or orthopedic abnormalities were detected. The study was performed with approval of the University of Minnesota Institutional Animal Care and Use Committee.

Underwater treadmill training - All horses used in this study had previous land treadmill experience as part of an unrelated study. Since it has been shown that horses reach a steady state gait within the first 4-6 sessions of water treadmill exercise,[70] horses were walked in the UWTM[a] for a total of 6 training sessions (1/2 hour per session) before data was collected. Xylazine[b] (0.2 mg/kg, IV) was administered for the first two training sessions if horses showed anxiety or were reluctant to walk on the UWTM. Horses were initially walked with < 1 cm of water (minimum amount of water to run the UWTM) to allow acclimatization to the UWTM. Over the subsequent training sessions horses were individually acclimated to walking on the UWTM at different water levels (up to the hind fetlocks, tarsi, and stifles). The speed of the treadmill was maintained at 0.9 m/s during each training session and for all data collection. Water temperature was not controlled in this study but it ranged from 15 to 21 Celsius degrees throughout.

Kinematic measurement procedure – In order to track movement of the distal limbs under water, zinc oxide was applied to the skin since it does not readily dissolve in water. Four zinc oxide markers (2 cm in diameter) were placed on the left forelimb and left hind limb (the only limbs that can be analyzed through the windows while the horse is under water – Figure 1). Locations of skin markers were placed on the most lateral aspect of each limb, exactly over the center of rotation of each joint. Forelimb markers were placed at the level of: 1) proximal interphalangeal joint, 2) lateral condyle of the distal third metacarpus, 3) ulnar carpal bone and 4) 15 cm proximal to the ulnar carpal bone on the groove between the common and lateral digital extensor muscles on the radius (Figure 2a). Hind limb markers were placed at the level of: 1) proximal interphalangeal joint, 2) lateral condyle of the distal third metatarsus, 3) mid talus, and 4) 10 cm proximal to the tuber calcanei on the groove between the long and lateral extensor muscles on the tibia (Figure 2b). Locations of the skin markers were chosen based on other authors' recommendations,[43] with slight modifications due to the size of the windows on the side of UWTM. In other words, the distal marker had to be placed at the level of the proximal interphalangeal joint instead of the hoof and the proximal marker had to be placed in the middle of the tibia or radius instead of the proximal aspect of the bone to be able to analyze a complete stride at all water levels. Hair was clipped in these locations to ensure consistency of placement throughout the study.

Two-dimensional movement was recorded using a digital video camera[c] (6.0 mm lens) at 60 frames/sec while the horse was walked on the UWTM at four different water levels: < 1 cm of water (B), water up to the hind fetlocks (F), tarsi (T), and stifle (S). For the fetlock water level, the UWTM was filled up to the skin marker placed on the lateral condyle of the distal third metatarsus. For the tarsal water level, the UWTM was filled up to the skin marker placed on the mid talus. For the stifle water level, the UWTM was filled up to the tibial plateau of each horse (manually palpated). Video was recorded from the left side of the UWTM through one of the two transparent plastic windows that allows visualization of the horse's limbs while under water (Figures 1 and 3). Data collection was completed in 2 sessions over different days (one for the forelimb and one for the hindlimb). Before each session, a rectal exam was performed on each horse prior to being loaded into the UWTM to evacuate feces from the rectum. This was performed to minimize the risk of water contamination with feces, which can obscure marker identification during tracking. For the first session, the digital video camera was positioned on a tripod perpendicular to the front window (at 152 cm from the ground, and at 140 cm away from the UWTM) that allowed visualization of the left forelimb (Figures 1 and 3). Due to the reduced size of the window (90 x 70 cm), the camera had to be angled 30 degrees down in order to be able to capture the most distal marker (proximal interphalangeal joint) of the limb (Figures 1 and 3). Skin markers were illuminated by a 300W halogen lamp positioned close to the window, in approximately 45º angle so the light did not reflect back. After allowing horses to adjust for 5 minutes at each water level, 10 complete strides of the left forelimb without interruptions were videotaped for each water level (B, F, T, and S consecutively). During the second session, the same settings (camera angle and distance from the UWTM) and videotaping procedure were repeated through the rear window (90 x 70 cm) that allowed visualization of the left hind limb. Each horse's data was collected in approximately half an hour in each session over different days to prevent the gait from changing due to fatigue.

Figure 1. Photograph of a horse being recorded while walking on the UWTM with water up to his stifle. A digital video camera can be observed on the left side of the image (red arrow) that is positioned in front of the window that allowed visualization of the left forelimb. Illumination is provided by a 300W halogen lamp positioned close to the window so the light did not reflect back.

Figure 2. Photographs of a horse after being walked on the UWTM for data collection. Observe the locations of the skin markers on the fore (A) and hind (B) limbs used to define the body segments (blue lines) used to determine joint angles. Measured angles of each joint are represented by a white line.

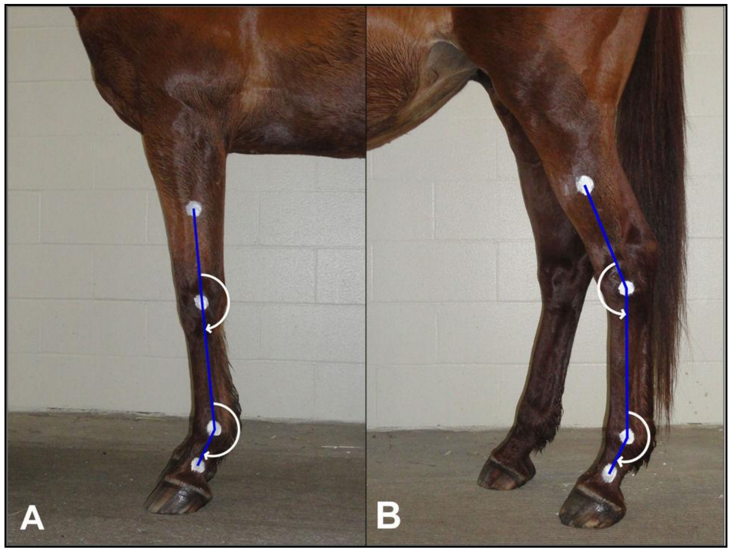


Figure 3. Photograph of a horse on the UWTM with water up to his stifle. This photograph is taken from the perspective of the camera being used to collect data (highlighted by the red arrow in Figure 1) to demonstrate how well the markers could be identified.

Two-dimensional kinematic analysis was performed using the DMAS Equine Gait Trax system[d]. Software calibration was performed at the beginning of each session by the use of a known distance marked on the windows of the UWTM. One stride was defined as complete foot contact with the belt (heel and toe) to the subsequent complete foot contact of the same limb. Within a stride, stance duration was described as the number of frames within a stride in which there was contact of the foot with the belt from heel down to breakover. Duration of the stance and swing phases of the fore and hind limbs were calculated for each horse under each water level. The ten videotaped strides were reviewed and only the five strides with the least amount of water splashing and best visibility of skin markers were used for tracking and calculation of stride percentages. Tracking of the skin markers was carried out by a combination of an automatic and manual method to be able to create body segments that represented the distal limbs and joints. Each frame of each stride was reviewed manually by the same person (J.L.M.A), and markers were magnified to ensure that the center was selected appropriately. The center of the marker was selected manually in all frames in which the software did not place them exactly in the center of the marker (approximately 90% were selected manually, and 10% found correctly by the software). For each individual complete stride, maximal flexion and extension angles of each joint of interest were calculated based on the rotation of the proximal and distal body segments around the palmar/plantar (carpus and fetlocks) and dorsal (tarsus) aspects of the joints using the inverse tangent function (Figure 2a and b). Range of motion (ROM) of the evaluated joints, represented by the relative inter-segmental motion, was calculated for each stride of each horse in each water level as maximal extension minus maximal flexion.

A post-hoc error calculation was performed for the camera angle and water refraction by placing a right angle in the areas of maximum flexion and extension of each joint (fetlock region and carpus/tarsus region). The right angle had 2 cm diameter markers on both branches and center of rotation, and was analyzed (using the same software and settings as in the study) at each location with the UWTM static with no water, partially submerged in water (2 markers in the water and 1 marker out the water) and completely in water as would occur with each different water level. To determine if there was an error based off of the camera angle itself, additional measurements using the same conditions described above were collected with the camera placed perpendicular to the UWTM. A total of 50 measurements were collected and the markers on the right angle were tracked. The error was determined based off of the deviance from 90 degrees, and the average error identified at each location within the window and at each water level was subsequently corrected in the data before statistical analysis.

Statistics - Mean ± SD of maximal flexion and extension angles, joint ROM, and the stance and swing percentages of each water depth were calculated by first averaging 5 strides of each horse, and then combining the average of those 5 strides for all horses at each water level. Extreme studentized deviate tests were conducted on the 5 strides analyzed for each joint for each horse under each water level to identify outliers, which were subsequently removed from further analysis. Stance and swing temporal data was transformed to percentages. Normality of the data was assessed using the Shapiro-Wilk normality test. Differences between the 4 water levels for each joint of interest were determined using a repeated-measured ANOVA with a Tukey-Kramer's multiple comparison test. Statistical significance was set at $p<0.05$. All data were analyzed using a statistical software package[e].

Results

The amount of error that was present based on our 2-D kinematic analysis system was < 3 degrees. This includes the error based on the camera angle and water refraction. There were no differences in error with the camera positioned at a 30 degree angle versus being perpendicular to the UWTM. The amount of error was different based on the location and water level. The location where flexion generally occurred for the fetlocks as well as the carpus/tarsus demonstrated less angle than 90 degrees (87.6 to 90 degrees) that varied based on the joint of interest and water level. The location where extension generally occurred for the fetlocks as well as the carpus/tarsus demonstrated greater angle than 90 degrees (90 to 92.9 degrees) that varied based on the joint of interest and water level. The average error calculated for each joint in each location (flexion/extension) for each water level was used to correct the peak flexion/extension data points of the results presented below.

Kinematic analysis showed that walking horses in any depth of water (F, T, or S) in the UWTM, resulted in a significant (all $P<0.001$) increase in maximal flexion in all evaluated joints compared to walking with no water (B) (Figure 4). When comparing maximal joint flexion within the three water levels (F, T, and S), the greatest flexion of the carpus and fetlocks (fore and hind) was achieved with T and the greatest flexion of the tarsus was achieved with T and S (Figure 4; Table 2).

During walking, maximal extension was significantly ($P<0.001$) greater for the carpus in T, for the tarsus in S, and for both fetlocks in F compared to walking in no water (B) (Figure 4). Conversely, maximal extension was significantly less for the fore fetlock ($P<0.01$) in T compared to walking in no water (B) (Figure 4). When comparing maximal joint extension within the three water levels (F, T, and S), the greatest extension of the carpus occurred with T, the greatest extension of the tarsus with S, and the greatest extension of the fetlocks with F, which were all significantly ($P<0.01$) different compared to the other two water levels (Figure 4; Table 2).

Overall ROM was significantly ($P<0.001$) greater for all evaluated joints when horses were walked in water (F, T, and S) compared to walking in no water (B) (Figure 4). Additionally, the greatest carpal ROM was attained with T and the greatest tarsal ROM with S. The greatest fore and hind fetlock ROM was attained with F and T (Figure 4; Table 2).

Significant differences were observed in the stance and swing percentages of the fore and hind limb strides between all water levels (Table 3). As the water level increased the fore and hind limb stance percentage of the stride decreased, whereas the swing percentage of the stride increased as the water level increased (Table 3).

Figure 4. Maximal flexion (left-hand column) and extension (middle column) angles, and ROM (right-hand column) of the carpus (1st row), tarsus (2nd row), fore fetlock (3rd row), and hind fetlock (4th row) joints of healthy horses (n=9) walking on the underwater treadmill without water (B; white bar) and with water (gray bars) up to the hind fetlocks (F), tarsi (T), and stifles (S). Mean + SD are presented in the bar graphs. Significance denoted as: * P<0.05, ** P<0.01, and *** P<0.001.

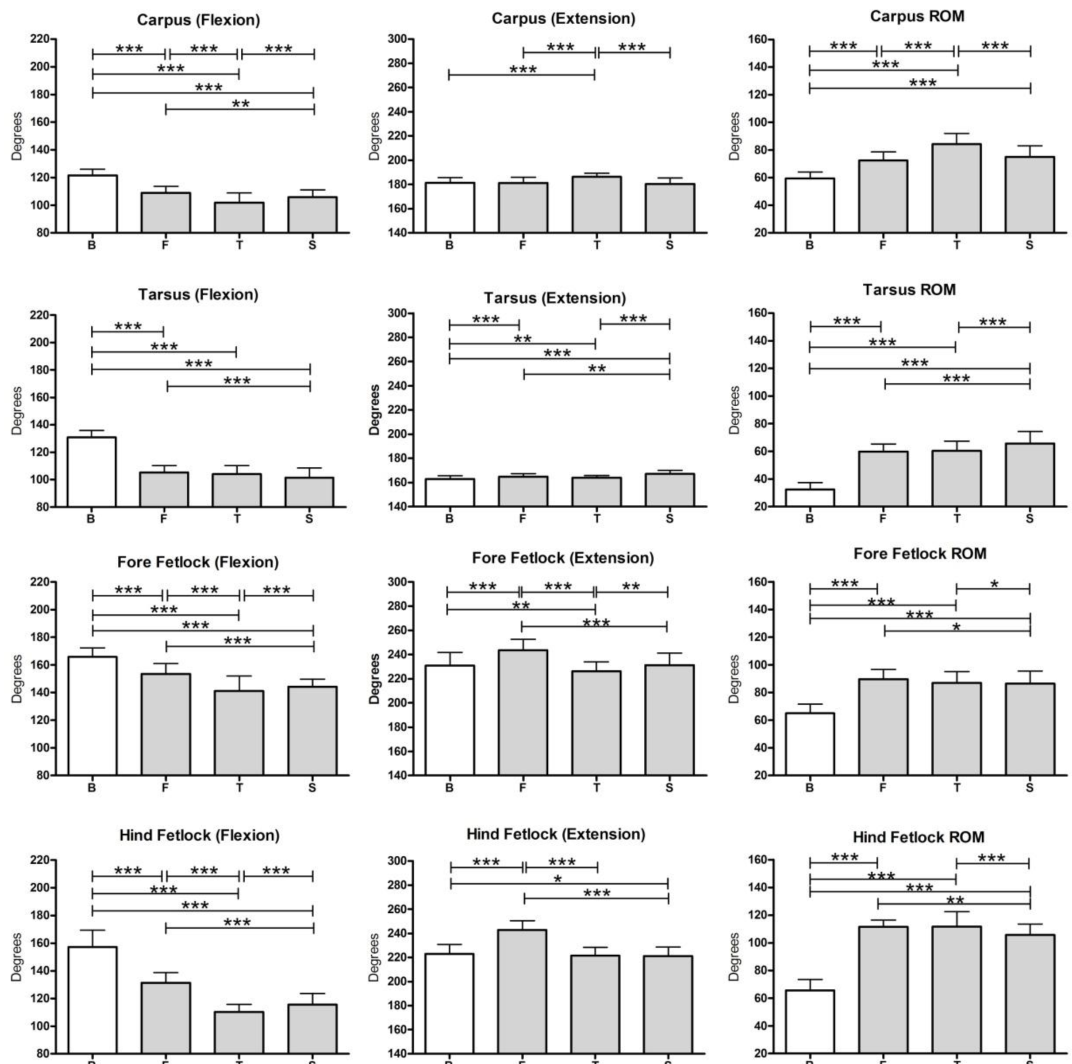


Table 2. The overall gain in flexion, extension, and joint range of motion (ROM) are indicated (in degrees) for each water level in which the evaluated joint achieved the greatest flexion and/or extension to demonstrate how much ROM can be increased at different water levels in the underwater treadmill.

Joint	**Water level**	**Flexion**	**Extension**	**ROM**
Carpus	Tarsal water depth	20	5	25
Tarsus	Stifle water depth	29	4	33
Fore fetlock	Fetlock water depth	12	13	25
Hind fetlock	Fetlock water depth	26	20	46

Table 3. Mean ± SD of percentages of stance and swing phases of the fore and hind limbs of 9 healthy horses walking on the UWTM with four different water levels; <1cm of water (B), fetlock (F), tarsus (T), and stifle (S).

Variable (%)	B	F	T	S
Stance forelimb	67.2 ± 1.9^{a}	63.9 ± 1.3^{b}	60.0 ± 1.1^{c}	57.2 ± 1.0^{d}
Swing forelimb	32.4 ± 1.7^{a}	35.8 ± 1.3^{b}	39.9 ± 1.1^{c}	42.7 ± 1.0^{d}
Stance hind limb	65.6 ± 1.7^{a}	62.0 ± 1.4^{b}	60.0 ± 2.5^{c}	58.2 ± 2.2^{d}
Swing hind limb	34.3 ± 1.7^{a}	37.9 ± 1.4^{b}	39.9 ± 2.5^{c}	41.8 ± 2.2^{d}

$^{a–d}$ Within a row, values with different superscript are significantly ($P<0.01$) different from each other.

Discussion

Our results showed that walking horses in water increases overall ROM of the carpus, tarsus, and both fetlocks (fore and hind), mainly due to an increase in joint flexion. This increase occurred to a different extent in each joint depending on the water level. Additionally, greater joint extension of the evaluated joints was observed in certain water depths. These findings confirmed our first hypothesis and provide objective data that support the suggestion that an UWTM can be used to encourage joint ROM in horses.[70] Conversely, our second hypothesis was partially refuted because joint flexion and extension did not consistently increase with increasing water depth in all joints.

Clinicians and physical therapists try to encourage joint ROM in conventional footing surfaces using other equine rehabilitation techniques such as passive flexion and extension, walking over poles or cavalletis, and attachment of tactile stimulators or weights to the distal limb.[20,71] Some of these techniques have been extrapolated from human or small animal rehabilitation,[72] and little information is available regarding how much they increase joint ROM in horses. Recently, two studies have focused on the effects of the attachment of tactile stimulators and/or weights (700 g) around the pasterns of horses, showing a significant increase in flexion of the fetlock, tarsus, and stifle at the trot when these devices were applied to the hind limbs.[42,73] In contrast, several studies have shown that the addition of weights to the front limbs does not significantly increase the flexion of the carpus or fore fetlock.[74-76] In our study, the UWTM increased ROM of all evaluated joints. In addition, at certain water levels (S and T) the gain in flexion of the tarsus and hind fetlock (29 and 47 degrees, respectively) was similar or greater to that reported at the trot when using tactile and weighted stimulators applied around the hind pasterns.[42] Currently, objective data about rehabilitation techniques is lacking in horses, and the amount of flexion/extension needed to help a clinical case is unknown. This study provides data on how much sound horses can flex and extend the distal limb joints walking in water, and now further research in clinical cases with reduced limb motion is warranted. In our study, walking in the UWTM with specific water depths also resulted in greater joint extension for the evaluated joints (Table 2), which has not been reported with other conventional rehabilitation exercises. However, the increases seen in extension of the carpus and tarsus were ≤ 5 degrees, likely because of the anatomical limits of these joints, and its clinical significance needs further research.[47] Therefore, the UWTM may have advantages over other techniques for early rehabilitation of acute musculoskeletal injuries because it not only encourages flexion of all joints but also some degree of extension (Table 2). Furthermore, UWTM rehabilitation provides the additional hydrotherapy benefits of buoyancy, viscosity, resistance, hydrostatic pressure, and surface tension.[41]

Human and small animal kinematic studies have demonstrated an increase in the ROM of distal limb joints when walking in water compared to land. Similar to our study, this increase has been reported to occur mainly due to an increase in joint flexion rather than extension. For instance, ankle and knee flexion was greater in people walking and running in water up to the waist than they did on land.[77] In dogs, flexion of the hip, stifle, tarsus, shoulder, and elbow was greater walking in the UWTM than walking on the land treadmill.[34] Small animal kinematic data have also demonstrated that higher water levels do not necessarily result in a greater flexion of joints. For instance, flexion of the canine hip, stifle and tarsal joints increased maximally when water level was at the stifles, but then decreased if water was added up to the level of the greater trochanter.[9] In our study, the greatest flexion of the fore limb joints (carpus and fore fetlock) occurred in T, which may be because horses walking in low water levels may attempt to elevate their limbs out of the water to avoid resistance. This did not occur at deeper water levels (i.e. S), potentially because the entire limb is submerged, and so the horse is unable to lift the limb above the water surface, and thus is forced to move the whole forelimb through the water instead. In the hind limb, the greatest flexion of the tarsus occurred with T and S. This finding may be caused by the synchronized movement of the reciprocal apparatus where the stifle and tarsus flex and extend simultaneously.[78] At these water levels (T and S), horses may still attempt to elevate their hind limbs to get their stifles out of the water to decrease resistance during motion, thus simultaneously increasing tarsal flexion.

Results of this study showed that water level affected flexion and extension of the joints differently, even in joints of the same limb. Thus, the evaluated joints reached the greatest ROM at dissimilar water levels. Additionally, the greatest flexion and the greatest extension of a joint (i.e. fore and hind fetlocks) did not necessarily happen at the same water level, resulting in less increase in overall ROM of that joint at one water level. This data suggests that equine clinicians and physical therapists should be aware of the effect of water level on the motion of joints and should consider its effects when designing a rehabilitation program, especially if the goal is to increase flexion and/or extension of a particular joint or limb. For instance, walking in water up to the tarsus would be indicated for a horse with reduced ROM of the carpus. A higher water level (i.e. S) would be recommended for horses in which tarsal flexion and extension are desired. In horses with decreased ROM of the fore or hind fetlocks, alternating exercise in two different water levels (T and F) may be recommended because walking in water up to tarsus would encourage flexion, and water up to the fetlock would provide more extension. These are general recommendations based on data from this study but it should be clarified that our population was mainly Quarter Horses, and although the Thoroughbred (similar height and weight) used in this study moved similarly, other breeds may have different increases in flexion and extension depending on water level. Additionally, the increase in activity of the different muscle groups involved in protraction and retraction of the limbs should be considered when choosing a water level, especially in the early rehabilitation period, to avoid muscular fatigue and/or injury of the untrained muscles.

In a recent study, horses walking in the UWTM at carpal and ulnar water depths were shown to have lower stride frequency and higher stride length of the forelimbs compared to walking in lower water levels.[70] Similarly, we evaluated stance and swing percentages of the stride and found that water level had a direct effect on these measurements. Our results showed that as the water height increased, stance percentage decreased and the percentage of the swing phase increased. At the trot, an increase in swing phase has also been reported in horses when hind limb flexion is encouraged by adding tactile stimulators and/or weights to the hind pasterns, causing an increase in flexion at the stifle, hock and hind fetlock joints.[42] Our results demonstrate that this effect can be achieved using the UWTM, and may be due to the effect of water resistance and/or buoyancy. At the water levels used in this study, water resistance was expected to increase along with water depth, because water resistance is proportional to the portion of a limb submerged in water. The effect of buoyancy has been evaluated in horses at high water (saline) levels, resulting in a reduction of 10% in body weight when water was at the level of the olecranon, and 75% when water was at the level of the tuber coxae.[12] At lower water levels, the effect of buoyancy has not been measured in horses, but in a canine study,[13] vertical ground reaction force only decreased by 9% after immersion to the tarsal joints and by 15% after immersion to the stifle joints. Therefore, the effect of buoyancy at the water levels used in our study was likely minimal.

Evidence of the benefits of an UWTM for rehabilitation of orthopedic patients is available in the human and veterinary literature. For instance, in people, water exercise has been shown to decrease joint effusion and pain after orthopedic surgery.[25,27] A recent study in people with total knee arthroplasty demonstrated that the benefits obtained using hydrotherapy (reduction in pain and stiffness, and improvement in function) were still identified in patients up to six months after discharge from the hospital.[79] In dogs, aquatic exercise after correction of cranial cruciate ligament rupture resulted in greater ROM of the stifle and tarsal joints than did walking on land.[31] Similarly, dogs after tibial plateau leveling osteotomy showed improvement in limb function when early intensive postoperative physical therapy included passive ROM and training on an UWTM.[33] Unfortunately, no similar studies are currently available in horses, so the impact of adding UWTM exercise to a rehabilitation protocol is unknown and needs investigation; however, the results of our study demonstrate that use of the UWTM is possible for the orthopedic patient because it stimulates an increase in the ROM of distal limb joints.

Several limitations due to infrastructural conditions can be identified in this study. Therefore, the results of this study may have been influenced by some factors which could not be avoided due to the constraints presented by the UWTM setting. This includes use of a 2D system, collection of left limb motion only, data collected in a skewed angle, and water refraction. The reader needs to understand that all of these components may make our angle data more relative than precise, but the authors made a number of efforts throughout the study in an attempt to reduce these factors and the variability created by them. In humans[80] and small animals[31], underwater kinematic analyses are performed using three dimensional systems, but this not possible in horses due to the confines of current UWTM facilities. We had to use a 2-D system to perform the kinematic analysis since data had to be collected through each window on the left side of the UWTM (Figure 1). However, the window size itself (90 x 70 cm) may have helped minimize the amount of error because the motion of each stride was contained within that small area. Conversely, when performing 2-D analysis with the horse walking over ground, motion data has to be analyzed over many meters which have the possibility for greater error. It is important to note that within our 2-D system only motion that occurred in the sagittal plane (plane of major limb movement) could be represented and may be affected if there is any non-sagittal movement that occurs during a stride. It is possible that walking in water may induce more non-sagittal motion of the limbs than walking over ground, which could add more error. Only the left fore and hind limbs could be evaluated because our UWTM does not have transparent windows on the right side. Despite this issue, results obtained from the left limbs should be able to be extrapolated to the right side because the walk is a symmetric gait and sound horses are expected to move their limbs symmetrically.[81] Other important factors that we could not eliminate in our study due to the constraints of the UWTM were the facts that the camera had to be angled 30 degrees down in order to be able to track the motion of the distal most marker, and that water refraction likely altered tracking of the motion as well. These factors likely reduced the sensitivity of our measurements. However, we attempted to minimize their effects within the system as much as we could. The same person marked all horses, filled the UWTM in all sessions, set up the video camera for each horse in each session, and manually tracked every single frame (moved back and forth between contiguous frames) in an attempt to ensure adequate central placement of the markers by the software. In addition, multiple strides (n=5) for each horse at each water level were collected in an attempt to minimize variability that would arise due to our data collection system. We attempted to correct for our camera position and water refraction by introducing a fixed angle (90 degrees) into the UWTM at all water levels and flexion and extension locations. This analysis allowed for further error correction in our data which should have further minimized variability from these sources, however, it does not reflect any potential error caused by motion of the treadmill, water turbulences, or limbs movement. Based off of this analysis, we believe the error of our set up and the effect of the water combined is less than 3 degrees for any joint at any water level, and our corrected results are representative of the general motion of the distal limb in and out of the water. When comparing our corrected baseline results to those reported in other studies[59,60] where limb kinematics at the walk were evaluated over ground on sound horses, our means and standard deviations are very similar.

In conclusion, results of the present study showed that an UWTM should be considered for an equine rehabilitation program to increase the overall range of motion of the distal limb joints. Results of this study can be a useful reference for clinicians or physical therapists that are trying to encourage overall ROM or increased flexion or extension of a particular joint or limb since the water level affects the amount of flexion and extension of the joints differently.

Chapter 3

Comparison of flexion and extension of the distal limb joints of healthy horses when walking on three conventional footing surfaces

Chapter 3. Comparison of flexion and extension of the distal limb joints of healthy horses when walking on three conventional footing surfaces

Chapter Summary

Objective- To calculate maximal flexion and extension of carpus, tarsus, and fetlocks, and percentage of stride spent in the swing and stance phase of horses walking on three conventional footings.

Animals- Nine sound adult horses.

Procedures- Data of horses walking on hard ground (HD), soft ground (SF), and a land treadmill (LT) were recorded by one digital video camera and analyzed using 2-dimensional motion-analysis software. Retroreflective markers were placed on the skin at four anatomical locations on the left fore and hind limbs. Five complete gait cycles were analyzed. Maximal flexion/extension angles, and range of motion (ROM) were calculated for each joint, and percent of the stride spent in stance or swing phase were determined for each stride.

Results- Maximal flexion of the tarsus and hind fetlock was greater on LT and SF compared to HD, and carpus on LT compared to HD and SF. Maximal extension of the carpus was greater on HD compared to SF and LT, tarsus on HD and SF compared to LT, and both fetlocks on LT compared to HD and SF. The greatest overall ROM of the carpus and fetlocks was achieved on LT, and tarsus on SF. The stance percentage of the stride for the hind limb was statistically different between all surfaces.

Conclusions and clinical relevance- Walking surface influences flexion/extension of the carpus, tarsus, and fetlocks to a different extent. This data could help clinicians to decide which footing surface is best to walk an orthopedic patient in the early rehabilitation period.

Introduction

In equine orthopedic patients, joint stiffness and loss of limb function may occur from the progression of osteoarthritis or as sequelae to musculoskeletal injury. Several studies have reported reduced range of motion (ROM) in joints with osteoarthritis.[38-40] Similarly, an experimental study showed that joint ROM of the fetlock (i.e. metacarpophalangeal joint) of clinically healthy horses casted for 7 weeks was still restricted after 8 weeks of exercise following cast removal.[57] Thus, intensive physical therapy is often required in these patients to maintain, or improve joint mobility through maximizing flexibility of the soft tissues and encouraging full ROM of the affected joints.[20,71,82]

Exercises designed to promote joint ROM are particularly useful in the early rehabilitation period of orthopedic patients.[37] These exercises may help to prevent joint contracture and soft tissue adaptive shortening, reduce pain, enhance blood and lymphatic flow, and improve synovial fluid production and diffusion.[36] For this purpose, a wide variety of such therapeutic exercises and rehabilitation modalities are currently available for equine patients.[20] However, the selection of therapeutic procedures is often based on individual experience of the therapist, or extrapolation from human or small animal rehabilitation literature, because scientific data on equine therapeutic modalities are scarce.

Hand walking on hard or soft surfaces at increasing intervals is one of the first exercises recommended by most equine clinicians or physical therapists in the early rehabilitation period.[71] Hand walking is a low intensity exercise in which joint ROM is relatively limited. Therefore, therapists often recommend walking in alternating surfaces (e.g. soft and hard grounds), walking over poles or cavalletis, or the attachment of tactile stimulators and/or weights to the hind pasterns in order to encourage further joint ROM.[20,42,73] Additionally, the use of a land treadmill has been suggested as an alternative to in-hand walking because it provides the ability to exercise the horse on a non-slip surface with minimum concussion at a controllable speed.[20] However, to the authors' knowledge, there is no objective data on how walking a horse on different conventional footing surfaces may affect the ROM of the joints of the distal limb. Determination of the effect of walking surface on the flexion and extension of the distal limb joints would help clinicians and physical therapists when designing a rehabilitation program, especially of orthopedic patients with stiffness and decreased ROM of these joints.

Therefore, the objectives of this study were to: 1) calculate the maximal flexion and extension angles, and the ROM of the carpal, tarsal, and fetlock (fore and hind) joints of sound horses walking on three different surfaces: hard ground (HD), soft ground (SF), and on a land treadmill (LT); 2) calculate the percent of the stride spent in stance or swing phase; and 3) determine which surface provides the greatest flexion, extension, and overall ROM for each joint. We hypothesized that walking surface (HD, SF, and LT) would affect the flexion and extension of the distal limb joints as well as the percent of the stride spent in the swing phase differently. Additionally, we hypothesized that walking in soft ground would provide the greatest overall ROM of all joints.

Material and Methods

Horses - Nine clinically sound horses (8 Quarter Horses and 1 Thoroughbred) were included in the study. Mean ± SD age of the horses was 8.1 ± 4.3 years; mean weight was 486.6 ± 26.3 kg; and mean height at the withers was 150.1 ± 3.2 cm. It was determined that horses were healthy and not lame on the basis of a thorough physical examination and results of routine subjective lameness evaluation. The study was performed with approval of the University of Minnesota Institutional Animal Care and Use Committee.

Data collection- All horses used in this study had previous treadmill experience from an unrelated study, and they were acclimated to the other walking surfaces (HD and SF) and the surrounding environments by walking back and forth on an asphalt surface used for lameness evaluation (HD) and in arena footing (SF). Horses were always walked from the left side of the horse by the same experienced handler at a consistent speed and acceleration. During data collection, walking speeds were calculated using a wireless timing system[f] and trials were only considered acceptable if horses walked at 0.9-1.5 m/s with an acceleration of ±10%. At the end of each trial, the handler was informed of the mean speed and acceleration in an attempt to reduce variability. The speed of the treadmill[g] was maintained at 1.2 m/s (lowest possible speed) for data collection. In order to track the movement of the limbs on the different surfaces (HD, SF, or LT), four retroreflective spherical markers (3 cm in diameter) were taped to the skin over the center of rotation of each joint (lateral aspect), in defined anatomic locations on the left forelimb and left hind limb of each horse. Forelimb markers were placed at the level of: 1) proximal interphalangeal joint, 2) lateral condyle of the distal third metacarpus, 3) ulnar carpal bone and 4) 15 cm proximal to the ulnar carpal bone on the groove between the common and lateral digital extensor muscles on the radius (Figure 5a). Hind limb markers were placed at the level of: 1) proximal interphalangeal joint, 2) lateral condyle of the distal third metatarsus, 3) mid talus, and 4) 10 cm proximal to the tuber calcanei on the groove between the long and lateral extensor muscles on the tibia (Figure 5b). Locations of the skin markers were chosen based on other author's recommendations for gait analysis,[43] with slight positional modifications to mimic data collected in the underwater treadmill (Chapter 2) to allow for comparison. Modifications included placement of the distal marker at the level of the proximal interphalangeal joint instead of at the hoof and placement of the proximal marker in the middle of the tibia or radius instead of at the proximal aspect of the bone. Hair was clipped on these locations to ensure consistency of marker placement throughout the study.

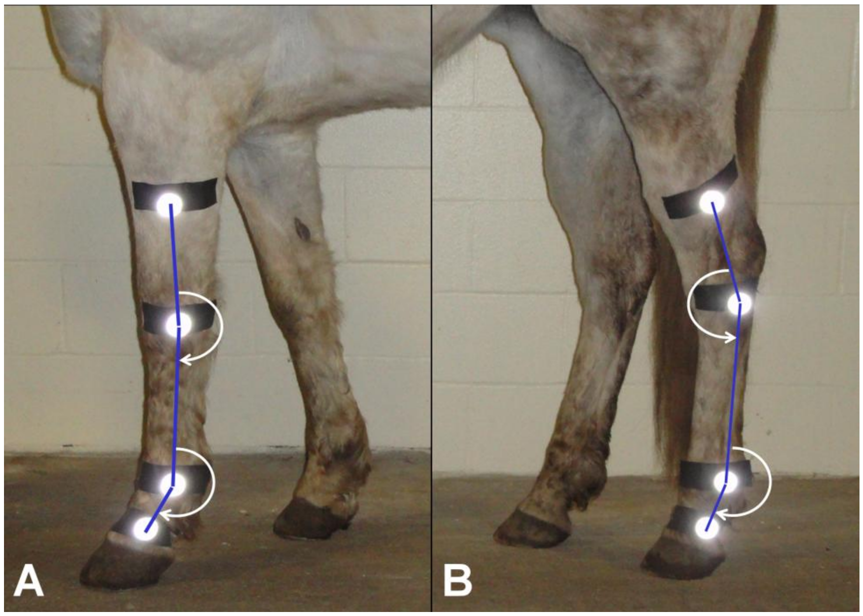
Two-dimensional movement was recorded using a digital video camera[c] (6.0 mm lens) at 60 frames/sec while the horse was walked on hard ground (HD), soft ground (SF), and on the land treadmill (LT). Video was only recorded from the left side of the horse for all surfaces to allow for comparison to data collected in the underwater treadmill (Chapter 2). Data collection was completed in 3 sessions (one for each surface). For the first session, the digital video camera was positioned on a tripod perpendicular to the lameness runway (at 152 cm from the ground, and 300 cm away from the runway). The camera was angled 30 degrees down to be able to compare results with data obtained in the underwater treadmill (Chapter 2). The retroreflective skin markers were illuminated by four 300W halogen lamps positioned close to the camera's field of view. After allowing horses to adjust by walking for 5 minutes at each surface, 10 complete strides of the left fore and hind limbs of each horse were videotaped. For the second session, the digital video camera and the halogen lamps were moved into the arena, and data was collected in this footing (SF) using the same settings (camera angle and distance from the horse) and videotaping procedure used in the lameness runway. During the third session, horses were videotaped walking on the land treadmill using the same settings (camera angle and distance from the horse) and videotaping procedure used for the other two testing surfaces (HD and SF). Data from each session was collected in three consecutive days (one session per day). Data for each horse on soft and hard ground was collected in approximately twenty minutes per horse per footing/surface. Data on the treadmill was collected in 10 minutes per horse.

Data analysis - Two-dimensional kinematic analysis was performed using the DMAS Equine Gait Trax system.[d] Software calibration was performed at the beginning of each session by the use of a known distance within the camera's field of view. One stride was defined as the distance from complete foot contact (heel and toe) with the ground to the subsequent complete foot contact of the same limb. Within a stride, stance duration was defined as the number of frames within a stride in which there was contact of the foot with the ground from heel down to breakover. Duration of the stance and swing phases of the fore and hind limbs were calculated for each horse for each surface. The ten videotaped strides for each horse for each surface were reviewed. From these ten strides, five strides were selected in which the horse completed a stride in the center of the camera's field of view, and these 5 selected strides were used for tracking motion and calculation of stride percentages. Tracking of the skin markers was carried out by a combination of an automatic and manual method to be able to create body segments that represented the distal limbs and joints. Each frame of each stride was reviewed manually by the same person (J.L.M.A), and markers were magnified to ensure that the center was selected appropriately. The center of the marker was selected manually in all frames in which the software did not place them exactly in the center of the marker (approximately 50% were selected manually, and 50% found correctly by the software). For each individual complete stride, maximal flexion and extension angles of each joint of interest were calculated based on the rotation of the proximal and distal body segments around the palmar/plantar (carpus and fetclok joints) and dorsal (tarsus) aspects of the joints using the inverse tangent function (Figure 5a and b). Range of motion (ROM) of each joint, represented by the relative inter-segmental motion, was calculated for each stride of each horse in each water level as maximal extension minus maximal flexion.

A post-hoc error calculation was performed for the camera angle by placing a right angle in the areas of maximum flexion and extension of each joint (fetlock region and carpus/tarsus region) in 10 different locations (5 at the fetlock level and 5 at the carpus/tarsus level) within the camera's field of view. The right angle had 2 cm diameter markers on both branches and center of rotation, and was analyzed (using the same software and settings as in the study) at each location. To determine the error based off of the camera angle itself, additional measurements using the same conditions described above were collected with the camera placed perpendicular to the different footings. A total of 30 measurements were collected and the markers on the right angle were tracked. The error was determined based off of the deviance from 90 degrees, and the average error identified at each location at each footing was subsequently corrected in the data (manually in each stride of each horse) before statistical analysis.

Statistics – Mean ± SD of maximal flexion and extension angles, joint ROM, and the stance and swing percentages of each surface were calculated by first averaging 5 strides of each horse, and then combining the average of all horses at each walking surface. Extreme studentized deviate tests were conducted on the 5 strides for each joint for each horse under each footing to identify outliers, which were subsequently removed from further analysis. Stance and swing temporal data was transformed to percentages. Normality of the data was assessed using the Shapiro-Wilk normality test. Differences between the 3 footing surfaces for each joint of interest were determined using a repeated-measured ANOVA with a Tukey-Kramer's multiple comparison test. Statistical significance was set at $p<0.05$. All data were analyzed using a statistical software package[e].

Figure 5. Photographs of a horse instrumented for data collection. Observe the locations of the retroreflective skin markers on the fore (A) and hind (B) limbs used to determine the body segments (blue lines) used to calculate the joint angles. Measured angles of each joint are represented by a white line.



Results

The amount of error that was present based on camera angle of our 2-D kinematic analysis system was < 2.2 degrees. There were no differences in error with the camera positioned at a 30 degree angle versus being perpendicular to the footing surfaces. The amount of error was different based on the location. The locations where maximal extension occurred for the fetlocks measured angles between 87.8 to 89.9 degrees, and for the carpus/tarsus angles between 88.3 and 90.2 degrees. The locations where flexion occurred for the fetlocks measured angles between 89.3 and 91.8 degrees, and for the carpus/tarsus angles between 88.8 and 91.1 degrees. The average error calculated for the different locations was used to correct the peak flexion/extension data points (of each stride of each horse in each footing surface) of the results presented below.

Kinematic analysis showed that the greatest maximal flexion for all joints was attained when horses were walked on LT. In this surface, the carpus showed a significant increase in flexion compared to the other two footing surfaces (HD and SF; Figure 6). Additionally, the tarsus and hind fetlock demonstrated a significant increase in flexion when horses walked on LT and SF compared to HD (Figure 6).

The greatest maximal extension of the most proximal joints (carpus and tarsus) was achieved when horses were walked on HD, which was significantly greater when compared to LT for both joints, and when compared to SF for the carpus (Figure 6). Walking on SF also caused greater extension of the tarsus when compared to LT. Conversely, the distal joints (both fetlocks) achieved the greatest maximal extension when horses were walked on LT, which was significantly greater than HD and SF (Figure 6).

The greatest overall ROM of the carpus and both fetlocks was achieved when horses were walked on LT, and the greatest ROM of the tarsus was achieved when walking on SF (Figure 6). ROM was significantly ($P<0.001$) greater for all joints when horses walked on LT compared to HD (Figure 6). Additionally, ROM for the tarsal joint was significantly greater when horses walked on SF compared to HD. ROM of the fore and hind fetlocks was also significantly greater when LT was compared to SF.

The percentage of the stride spent in stance phase decreased in the forelimb and hind limb walking on SF compared to HD and LT, although only the hind limb showed significant differences. In addition, LT showed a significantly greater percentage of the stance phase of the hind limb when compared to HD (Table 5).

Figure 6. Maximal flexion (left-hand column) and extension (middle column) angles, and ROM (right-hand column) of the carpus (1st row), tarsus (2nd row), fore fetlock (3rd row), and hind fetlock (4th row) joints of healthy horses (n=9) walking on hard ground (HD; white bar), soft ground (SF; gray bar), and on a land treadmill (LT; black bar). Mean + SD are presented in the bar graphs. Significance denoted as: * P<0.05, ** P<0.01, and *** P<0.001.

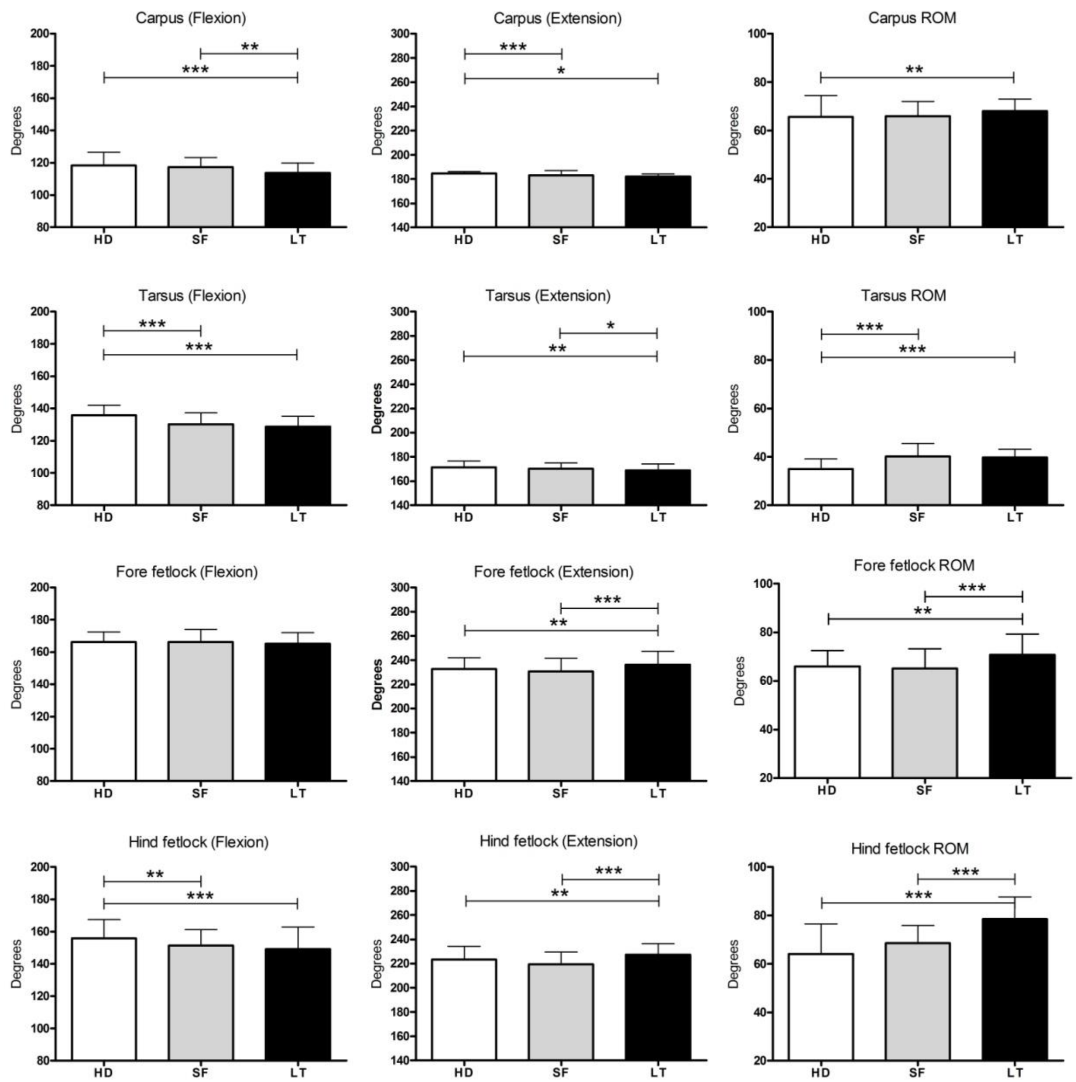


Table 4. Mean ± SD of percentages of the stance and swing phases of the fore and hind limbs of 9 clinically sound horses walking on hard ground (HD), soft ground (SF), and on a land treadmill (LT).

Variable (%)	HD	SF	LT
Stance forelimb	61.56 ± 0.7[a]	59.55 ± 1.4[a]	60.17 ± 2.7[a]
Swing forelimb	38.54 ± 1.2[a]	40.45 ± 1.4[a]	39.83 ± 2.7[a]
Stance hind limb	60.01 ± 1.0[a]	57.57 ± 1.2[b]	60.80 ± 1.4[c]
Swing hind limb	39.99 ± 1.0[a]	42.43 ± 1.2[a]	39.79 ± 2.2[a]

[a–c] Within a row, values with different superscript are significantly ($P<0.05$) different

Discussion

Results of this study found that the footing surface affects the flexion of the carpus, tarsus and hind fetlock and the extension of all evaluated joints (i.e. carpus, tarsus, fore and hind fetlocks) to a different extent when the horse is walking. In general, the treadmill was the best surface at increasing joint flexion and overall ROM, as well as extension of the fetlocks (fore and hind). However, walking on hard ground resulted in the greatest extension of the carpal and tarsal joints. These findings confirmed our first hypothesis, and are in agreement with other equine and human studies that have shown an impact of walking surface on limb kinematics.[83-86] Additionally, when soft and hard grounds were compared, soft ground was superior at increasing flexion and overall ROM of all joints except for the fore fetlock; hard ground was more effective at increasing joint extension. Our second hypothesis was refuted because walking on soft ground did not provide the greatest ROM for all evaluated joints.

Results of flexion and extension of the carpus, tarsus, fore and hind fetlocks of horses walking on a rubber surface have been reported by other authors.[59] In the present study, we measured flexion/extension angles of the distal limb joints of horses walking on asphalt, arena footing, and on a land treadmill, and our results are similar to those reported on a rubberized surface using a similar method of data collection.[59] In our study, despite the differences found between surfaces, changes in flexion and extension of the joints were less than 14 degrees. These increases, although subtle, may be enough to promote ROM in the early rehabilitation stage following injury, surgery, or a prolonged period of rest. However, other equine rehabilitation techniques such as passive flexion/extension, walking over poles or cavalletis, walking in an underwater treadmill (Chapter 2), or attachment of tactile stimulators and/or weights around the pastern of the hind limbs may provide additional joint flexion (increases up to 30-45 degrees), which may be more beneficial later on in the rehabilitation period.[31,42] Currently, objective data about rehabilitation techniques is lacking in horses, and to the author's knowledge, the amount of flexion/extension needed to help a clinical case is unknown at this time.

Results of this study showed that walking on the land treadmill causes the greatest flexion and extension of both fetlock joints, suggesting that this surface may be the most beneficial for promoting increased ROM of the fetlocks (Table 5). However, the greatest flexion and the greatest extension of the carpal and tarsal joints did not happen on the same surface (greatest flexion on LT, and greatest extension on HD), which suggests that clinicians may need to alternate walking in two different surfaces in order to encourage flexion and/or extension of the more proximal joints (Table 5). For instance, in horses with reduced motion of the carpus, alternating exercise on the treadmill and asphalt may be recommended because walking on the treadmill would encourage flexion, and walking on asphalt would provide more extension of the joint (Table 5). Additionally, in situations in which a treadmill is not available, alternating exercise in soft and hard ground may also encourage joint ROM because in general soft ground would promote more flexion, and hard ground would provide more extension. These are general recommendations based on data from this study but it should be clarified that our population was mainly Quarter Horses of similar sizes and fitness, and other breeds, sizes and fitness levels may have different increases in flexion and extension on conventional surfaces. Furthermore, horses that have been trained, especially to an advanced level, in a specific discipline may have changes unique to that discipline due to the specific outcomes of their training that were not able to be measured in this study.

Table 5. Footing surface at which the greatest flexion, extension, and overall range of motion (ROM) of each evaluated joint was achieved.

Joint	Flexion	Extension	ROM
Carpus	Land Treadmill	Hard Ground	Land Treadmill
Tarsus	Land Treadmill	Hard Ground	Soft Ground
Fore fetlock	Land Treadmill	Land Treadmill	Land Treadmill
Hind fetlock	Land Treadmill	Land Treadmill	Land Treadmill

Several studies have demonstrated the influence of walking surface on the stance and swing phases of the equine stride.[83,84,87,88] For instance, a study showed that at the walk, stride length was shorter on a flat turf track than on a treadmill.[83] Another study demonstrated that at the trot, the stance phase duration of the front limbs was shorter on a rubber surface than on a land treadmill.[84] Similarly, a more recent study showed that horses trotting on beach sand have a shorter stance phase than trotting on asphalt.[88] In the present study, we evaluated the percentages of the stance and swing phases on asphalt, arena footing, and the treadmill at the walk, and found that the length of the stance phase was shorter for horses walking on arena footing compared to asphalt, which agrees with the findings at the trot of previous studies,[84,88] and could be caused by an easier breakover in the arena footing compared to asphalt. We found that the stance phase of the hind limb was different for all evaluated footings, with the longest stance phase of the hind limb occurring while walking on the treadmill. This finding contrasts with the results of a similar study conducted at the trot, in which stance phase of the hind limb was shorter on the treadmill than on asphalt or rubber.[84] We did not find differences in the stance phase of the forelimbs, which indicate that walking surface has a lesser effect in the phases of the stride of the fore limbs.

Several limitations can be identified in this study, and most of them are due to the fact that the methodology for data collection was chosen to mimic data collected in the underwater treadmill study (Chapter 2). First, a 2-dimensional system was used to perform the kinematic analysis since it was the only option to collect the data through the windows of the underwater treadmill. This system (2-D) only reflects motion in the sagittal plane and may not be as accurate as a three dimensional system for certain kinematic parameters; however, a previous comparison of the two systems in horses at the trot found no differences between the two dimensional and three dimensional systems for angles of the joints evaluated in our study (i.e. carpus, hock, and fetlocks).[45] Another limitation of our study is the fact that the camera had to be angled 30 degrees down to be able to compare the data with the underwater treadmill study (Chapter 2). This factor likely reduced the sensitivity of our measurements because the majority of the joint movement occurs in the sagittal plane and videos were captured in a skewed angle. However, we attempted to minimize its effect within the system as much as we could. The same person marked all horses, walked the horses in the hard and soft grounds and run the treadmill, set up the video camera for each horse in each session, and manually tracked every single frame (moved back and forth between contiguous frames) in an attempt to ensure adequate central placement of the markers by the software. In addition, the video camera was placed very close to the footing surfaces having a field of view of 3.5 meters, and multiple strides (n=5) for each horse at each footing surface were collected in an attempt to minimize variability that would arise due to our data collection system. We attempted to correct for our camera position error by placing a fixed angle (90 degrees) at the different locations where the carpus, tarsus and fetlocks reached the maximal flexion and extension in each surface. This analysis allowed for further error correction in our data which should have further minimized variability from this source. Based off of this analysis, we believe the error of our set up is less than 2.2 degrees for any joint at any surface, and our corrected results are representative of the general motion of the distal limbs. When comparing our corrected baseline results to those reported in other studies[59,60] where limb kinematics at the walk were evaluated over ground on sound horses, our means and standard deviations are very similar (Table 1). Finally, although speed of the over ground trials was controlled with timers, walking speed may have influenced the results as walking speed has been shown to affect angular kinematics in horses.[89]

In conclusion, walking surface influences the flexion and extension of the carpus, tarsus, and fore and hind fetlock joints. This study provides objective data that can help equine clinicians and physical therapists to decide which footing surface is best to walk an individual orthopedic patient in the early rehabilitation period based on the location of that patient’s injury.

Chapter 4

General conclusions and future directions

Chapter 4. Conclusions and future directions.

Conclusions

This study showed that the underwater treadmill (UWTM) is a rehabilitation modality that can be used to encourage range of motion of the carpi, hocks, and both fetlocks (i.e. fore and hind) in the rehabilitation of equine patients. This finding is in agreement with other human and canine studies that have suggested that the UWTM is a useful technique to promote flexion and extension of the appendicular joints.

Results from this study showed that the UWTM can increase ROM of the carpus by 25 degrees, ROM of the hock by 33 degrees, the ROM of the fore fetlock by 25 degrees, and the ROM of the hind fetlock by 46 degrees. Based on these data, the UWTM seems to be the most effective rehabilitation modality to increase ROM of the distal limb joints if we compare it to all the other available techniques for which scientific information has been reported in horses.

Additionally, this study demonstrated that conventional footing surfaces such as asphalt, arena, and the land treadmill affect ROM of the carpus, hock, and fetlocks, with increases up to 14 degrees. These increases, although subtle, may be enough to promote ROM in the early rehabilitation stage following injury, surgery, or a prolonged period of rest. In general, the treadmill was the best conventional surface at increasing joint flexion and overall ROM. Soft ground was also superior at increasing flexion and overall ROM than hard ground. In contrast, hard ground was the most effective surface at increasing joint extension of the carpus and hock. The extension of the fetlocks (fore and hind) was maximal on the land treadmill.

When we compared the increases in flexion and extension of the joints in the UWTM versus on the conventional footing surfaces, we observed substantial differences. For instance, when comparing the two treadmills (UWTM and LT), the land treadmill was superior to the UWTM baseline (<1cm of water) at increasing flexion, extension, and overall ROM of all joints. This could be explained in part by the fact that the speed of the LT belt (1.2 m/s) was slightly faster than the UWTM belt (0.9 m/s), and research has shown that horses at higher speeds flex and extend their distal limbs more.[89] Also, in general, our study showed that the UWTM dramatically increases the flexion and overall ROM of the distal limb joints at all water levels compared to over ground exercise. However, increases in joint extension in the UWTM were similar to those observed in the conventional surfaces, suggesting that both rehabilitation modalities are comparable for this purpose.

The results of this study have been summarized in Table 6 to provide clinicians and therapists with objective data that should be considered when designing a rehabilitation program for an equine orthopedic patient.

Table 6. Maximal flexion and extension angles, and ROM of the carpus, tarsus, and fore and hind fetlocks joints of clinically sound horses walking in the UWTM without water (B), and with water up to the hind fetlocks (F), tarsi (T), and stifles (S), and walking on hard ground (cement, HD), soft ground (arena, SF), and land treadmill (LT). Values are expressed as degrees (mean ± SD).

Joint	Variable	B	F	T	S	HD	SF	LT
Carpus	Maximal Flexion	121.6 ± 4.6	108.8 ± 4.9	101.8 ± 7.1	105.8 ± 5.5	118.3 ± 8.2	117.2 ± 6.1	113.6 ± 6.2
	Maximal Extension	181.3 ± 4.4	181.1 ± 4.8	186.2 ± 3.1	180.4 ± 4.8	184.6 ± 1.6	183.2 ± 3.9	181.9 ± 2.5
	ROM	59.5 ± 4.4	72.4 ± 6.3	84.2 ± 7.8	74.9 ± 8.1	65.6 ± 8.9	65.9 ± 6.1	68.0 ± 5.1
Tarsus	Maximal Flexion	130.9 ± 4.9	105.3 ± 4.9	103.9 ± 6.3	101.3 ± 7.2	135.7 ± 6.4	130.3 ± 7.0	128.8 ± 6.5
	Maximal Extension	162.9 ± 2.6	164.8 ± 2.6	163.9 ± 1.8	167.0 ± 3.2	171.3 ± 5.3	170.2 ± 4.6	168.8 ± 5.2
	ROM	32.6 ± 4.9	59.9 ±5.6	60.4 ± 7.1	65.8 ± 8.6	34.9 ± 4.2	40.1 ± 5.5	39.7 ± 3.4
Fore fetlock	Maximal Flexion	165.9 ± 6.4	153.4 ± 7.7	141.1 ± 10.9	144.3 ± 5.4	166.2 ± 6.2	166.2 ± 7.9	165.0 ± 7.1
	Maximal Extension	231.0 ± 10.7	243.6 ± 8.9	226.0 ± 8.0	231.2 ± 9.8	232.6 ± 9.3	230.9 ± 10.9	236.2 ± 11.2
	ROM	65.0 ± 6.7	89.8 ± 6.8	86.8 ± 8.4	86.4 ± 9.1	66.0 ± 6.6	65.1 ± 8.2	70.7 ± 8.7
Hind fetlock	Maximal Flexion	157.2 ± 12.3	131.2 ± 7.4	110.1 ± 5.7	115.5 ± 8.2	155.8 ± 11.6	151.3 ± 9.9	149.2 ± 13.7
	Maximal Extension	222.8 ± 7.9	242.8 ± 7.6	221.6 ± 6.9	221.1 ± 7.5	223.3 ±11.2	219.4 ± 10.2	227.3 ± 9.3
	ROM	65.7 ± 7.9	111.4 ± 5.1	111.6 ± 10.9	105.6 ± 8.1	64.1 ± 12.5	68.6 ± 7.3	78.6 ± 9.2

Future directions

This study provides valuable information on how the water level affect the flexion/extension angles, and range of motion (ROM) of the carpi, hocks, and fetlocks of healthy horses walking in the underwater treadmill (UWTM). However, the effect of water level on the other distal limb joints (i.e. pastern and coffin joints), and the proximal joints (i.e. elbow, shoulder, stifle and hip) still needs to be determined. Unfortunately, this information cannot be obtained in our current UWTM because it is not possible to videotape the remaining joints through the small windows that the treadmill has on the left side. Thus, this is a pending study that we would like to do in the future if a different design of UWTM becomes available in the market, and any of our collaborators have access to it.

Currently, objective data about rehabilitation techniques is lacking in horses, and the amount of flexion/extension needed to help a clinical case is unknown. This study provides data on how much the distal limb joints of sound horses can flex and extend while walking on conventional surfaces and in the UWTM with different water levels. So, now that we have a deeper understanding on how UWTM can be used to encourage joint ROM in healthy horses, we would like to further evaluate the effect of the UWTM in orthopedic patients, and find out what ROM is needed to clinically influence patients. For this purpose, we would like to evaluate the effect of UWTM exercise in the rehabilitation of horses that have had a limb immobilized (casted) for a long period of time. This is a population of horses that often develops stiffness and loss of joint mobility as a consequence of adaptive shortening of the soft tissues due to the immobilization. For instance, a recent experimental study in which a metacarpophalangeal joint (i.e. fetlock) was casted for 7 weeks showed that joint ROM was still restricted after 8 weeks of treadmill exercise following cast removal.[57] Therefore, we would like to perform a similar study to assess the value of adding water treadmill exercise as part of the rehabilitation of horses that have had a limb casted. In this future study, we would like to rehabilitate horses with decreased ROM of the fetlock using the UWTM with different water levels. This way, we should be able to identify which water level is the best to rehabilitate a clinical patient with decreased fetlock motion and determine what ROM is needed to rehabilitate this specific joint.

Besides these additional studies on the underwater treadmill, this project has raised our curiosity in the kinematics of horses during swimming. This is another method of hydrotherapy that has been used for training and conditioning of race horses for many years.[6,7] and is now gaining popularity as a rehabilitation method for some musculoskeletal conditions. So far, there is no scientific information on the kinematics of horses during swimming, although canine studies have showed that this modality encourage the ROM of multiple joints.[31] We would like to design a research project to evaluate the kinematics of horses during swimming, and calculate the flexion and extension angles of several joints. This information combined with the data of the underwater treadmill could be used by equine clinicians and physical therapist to design better and more specific rehabilitation programs of horses with orthopedic lesions.

Footnotes

a) Equine Aquapacer, Ferno Veterinary Systems, Inc., Wilmington, OH.

b) Lloyd Laboratories, Shenandoah, IA.

c) IDS Imaging Development Systems GmbH, Obersulm, Germany.

d) Motion Imaging Corporation, Simi Valley, CA.

e) SAS/STAT®, v9.2 SAS Inst. Inc., Cary, NC.

f) Polaris Wireless Timer; FarmTek Inc, Wylie, TX.

g) Säto, Knivsta, Sweden.

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