UNIVERSITÀ DEGLI STUDI DI PADOVA
Department of Comparative Biomedicine and Food Science

First Cycle Degree (B.Sc.)
in Animal Care

The Role of Gait Analysis in Veterinary Rehabilitation of Dogs

Supervisor
Prof. Lieta Marinelli

Submitted by
Jarrod Pedro de Vos
Student n.
2018153

ACADEMIC YEAR 2023/24

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Abstract

Gait analysis is essential in veterinary rehabilitation, providing a comprehensive assessment of a dog's movement to identify abnormalities and develop rehabilitation programs. It is crucial for diagnosing pathologies affecting locomotion and monitoring rehabilitation effectiveness, ensuring optimal recovery and improved quality of life. Canine anatomy, particularly the musculoskeletal system, provides a fundamental understanding of gait biomechanics and locomotion.

By understanding canine locomotion, including different gait types, biomechanical functions, and patient related factors influencing movement (breed, age, health conditions, etc.), a therapist can perform a comprehensive gait analysis through subjective and, or objective methods, such as visual observation, kinematic analysis, and force plate analysis. This provides insights into a dog's health and enables the identification and diagnosis of gait issues, including orthopedic conditions like hip dysplasia and cruciate ligament ruptures, and neurological disorders such as degenerative myelopathy. Rehabilitation interventions, including manual and physical therapy, hydrotherapy, and electrotherapy, target recovery of specific biomechanical functions by strengthening muscles, improving joint range of motion, and enhancing neuroplasticity. These modalities are often used in combination to optimize recovery and avoid compensatory effects.

Early intervention of a multimodal approach allows for optimal recovery of localized conditions while maintaining whole-body health to avoid compensatory secondary effects of an injury. Using gait analysis to assess patients throughout rehabilitation provides feedback on intervention effectiveness, and enables adaptation to the patient's needs. Additionally, maintaining animal welfare standards is important to ensure humane interventions that minimise pain and discomfort throughout the rehabilitation process.

A comprehensive understanding of canine anatomy and biomechanics, combined with practical application of gait analysis, enables veterinary professionals to provide optimal care for dogs during gait rehabilitation, improve patient outcomes and enhance their overall well-being.

1. Introduction

1.1. Canine Anatomy & Optimal Structures for Locomotion

The domestic dog is considered to be one of the most phenotypically and morphologically diverse mammalian species, demonstrating a wide diversity in breed types and forms. With the physical structure and overall appearance being phenotypically constant within each specific breed, while being considerably different from breed to breed (Boyd, 2017). The variations of physical structure and functional morphology amongst the species directly affects their locomotory characteristics and capabilities.

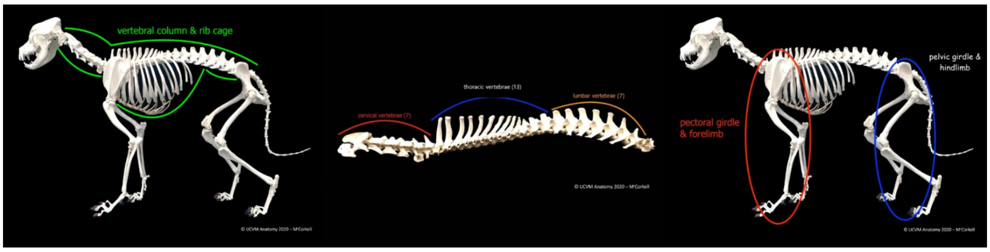

Fig. 1.1.1. Canine skeleton. Left: Axial skeleton. Middle: Vertebral column. Right: Appendicular skeleton (University of Calgary, 2024)

Investigating canine anatomy, specifically the skeleton of the domestic dog, can be divided into the axial skeleton, vertebral column and the appendicular skeleton (Figure 1.1.1). The axial skeleton consists of the skull, mandible, vertebrae, the ribs and sternum which provides structural and postural support and protects vital organs while serving as an attachment site for muscles. More specifically, the highly specialised skull housing the brain and sensory organs, such as the eyes and ears, is made up of the cranium and smaller facial bones. The dog's vertebral column is a series of interconnected vertebrae that protects the spinal cord which is divided into five regions that consists of 7 cervical vertebrae (C1-7) to support the head and neck; 13 thoracic vertebrae (T1-13) where each vertebrae is directly connected to its corresponding rib to form the rib cage; 7 lumbar vertebrae (L1-7) to support the lower back; 3 sacral vertebrae (S1-3) which are fused to form the sacrum and is connected to the pelvis and caudal vertebrae which can vary (generally 18-25) depending on the breed and its relevant tail length. In addition to protecting the dog's spinal cord, the vertebral column's structure facilitates flexibility and agility as well as a point for muscle attachment for the relevant locomotion. The rib cage is made up of 13 pairs of ribs that protects the vital organs such as the heart and lungs. The first nine pairs of ribs, connected to T1-9, are attached to the sternum while the remaining four pairs (T10-13) are considered 'floating ribs' as they are only connected to the vertebral column, (Hermanson et al., 2020). It is important to consider that even though slight variances are found between breeds in the shape of certain bones and the specific number of vertebrae, the overall structure and function of the axial skeleton remains consistent. The dog's appendicular skeleton is made up of the bones of both the fore-and-hind limbs and girdles that attach the appendicular skeleton to the axial skeleton, providing dogs with their long, slender appearance (Bello and Wamakko,2021). The appendicular skeleton is crucial as it enables a dog's locomotion and propulsion as well as a support for their balance. The structure of the forelimb (Figure 1.1.2), commonly referred to as the thoracic limb, is composed of the scapula and the

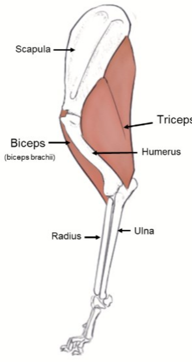

Fig 1.1.2. Canine forelimb (University of Calgary)

humerus to form the shoulder joint which provides a wide range of motion through relevant musculature such as the biceps which enables flexion of the shoulder and elbow joints; the triceps which enables extension of the shoulder and elbow joints; as well as shoulder protraction, with pectoralis muscles, and retraction, with latissimus muscles. The radius, primarily a weight-bearing bone, and the ulna, thinner and serving as a muscle attachment site, make up the bones of the forearm. Several small carpal bones make up the carpus joint to provide flexibility and shock absorption. Metacarpal bones form the metacarpus which resembles the 'palm' of the paw and the phalanges make up the five digits including the dew claw found only on the forelimbs. Together these bones facilitate the dog's distinct digitigrade locomotion (Hermanson et al., 2020). The forelimbs of a dog are primarily responsible for weight-bearing of the front half of a dog's body, especially during standing and walking; changing direction and other agile movements; as well as fine motor skills such as digging and clawing.

The structure of the hindlimb (Figure 1.1.3), commonly referred to as the pelvic limb, is composed of the pelvis as a strong and stable base for the hindlimbs, enabling the attachment of powerful muscles such as the hamstrings and quadriceps. The femur articulates with the pelvis at the hip joint to provide a wide range of motion and powerful propulsion. Additionally, the femur articulates with the tibia, for weight-bearing, and the fibula, serving as a muscle attachment site, along with the patella to form the stifle joint, which acts as a hinge joint following flexion of the limb due to the hamstrings and extension due to the quadriceps. The hock or tarsus is composed of several tarsal bones and is responsible for flexibility and shock absorption. The metatarsal and phalange bones make up the hindpaw and each paw's four digits which facilitates the dog's digitigrade locomotion (Hermanson et al., 2020).

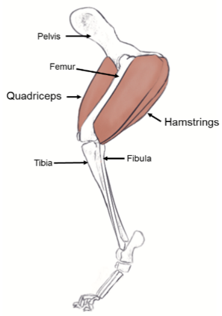

Fig 1.1.3. Canine hind limb (University of Calgary)

While the basic skeletal and muscular structure of dogs is relatively consistent, there are several normal anatomical variations that can influence a dog's gait. These variations are often breed-specific and follow the function of the breed. Variations of specific bone shapes and sizes, particularly the length of the humerus, will impact the gait as a shorter humerus leads to shorter strides and increased concussive forces through the elbow joint, while variations of bone density will influence a dog's overall strength and weight-bearing capabilities (M Christine Zink et al., 2018). The relevant limb length and proportion can vary between long-legged breeds, such as greyhounds, and short-legged breeds, such as dachshunds. Typically greyhounds possess longer limbs, with an emphasis on longer hindlimbs, giving rise to their larger stride length and increased speed, while dachshunds with shorter limbs, particularly forelimbs, have a limited stride length and ground clearance (Budras et al., 2010). As a result of structural variations of bones, relevant joint angulations may vary between breeds. An increased angulation of the shoulder joint will present a higher held head but will reduce the range of motion, shortening the stride length and increasing concussive forces. An increased angulation of the pelvic limb will result in longer stride lengths but increased pelvic instability, causing less accurate paw placements and slower turning capabilities. Alternatively, minimal pelvic limb angulation enables a dog to make faster turns at the expense of increased pressure on the stifle joint (M Christine Zink et al., 2018). Lastly, muscle mass and fibres determine a dog's locomotion capabilities by influencing a dog's ability to generate power, agility and to sustain locomotion. Variations of muscle mass may be a result of an injury or degeneration, while particular muscle fibres may vary between breeds. Following their function, greyhounds possess deep-back musculature and a higher proportion of fast-twitch muscle fibres allowing for increased speed and agility, while endurance-focused breeds such as huskies possess a higher proportion of slow-twitch muscle fibres (Guy and Snow, 1981).

A good understanding of the dog's unique anatomical structures and functions enables a trained professional to further investigate the quality of gait through a gait analysis and identify how a dog's gait is affected by anatomical variations. Professionals are able to decide whether the variations are within the breed's standard or if they can be labelled as lameness indicating potential orthopaedic or neurological conditions. Any abnormality or dysfunction, in a joint or segment of the skeletal structure and musculature, may result in an inability to carry out certain dynamic and static responsibilities, which could cause asymmetries and discrepancies in the timing and displacement of limbs resulting in inefficient locomotion and lameness (Gillette and Angle, 2014).

1.2. Basics of Canine Locomotion & Gait

During generations of research into Animal Sciences and close interactions with domestic dogs, a deeper understanding of dog locomotion has emerged. Dogs are required to perform a wide range of activities in daily interactions with their environment. From walking to jumping; swimming to digging and climbing, a dogs' four paws represent the point of contact with the surface and are responsible for traction and absorbing shock. While their strong and stable claws allow for digging and climbing, their limbs are primarily used for locomotion. Dogs are dependent on their powerful leg muscles for propulsion and the relevant muscular system allows for coordinated patterns of contractions and relaxation in order to produce the movement necessary. A dog's nervous system is important in controlling the coordination of the muscular patterns by sending and receiving sensory inputs between the brain and the muscles, ensuring a smooth and efficient synergistic effort of the bones, joints and neuromuscular system to move, stop and stabilise the body. The coordinated activation of the neuromuscular system rhythmically acts on the skeletal segments to produce fluid and symmetric motion of each joint in terms of concentric, eccentric and isometric muscle contractions. The dog's musculoskeletal system is responsible for continuously supporting body weight, absorbing external forces, maintaining posture and balance, and transferring the centre of gravity. The ability to properly carry out these static and dynamic responsibilities produces efficient and fluid locomotion (Gillette and Angle, 2014).

The gait of an animal describes the use of a combination of joints and skeletal musculature to perform and repeat certain whole-body movements, resulting in the synergistic locomotion for a selected gait. According to Gillette and Angle a dog's gait is made up of a series of repeated strides where each limb undergoes a step cycle. A step cycle (Figure 1.2.1) is divided into the stance phase, where the foot is in contact with the ground, and the swing phase, where the foot is in the air. The stance phase includes an initial period of the braking force created by making contact with the surface and a second period of propulsion in preparation for the swing phase. The swing phase can be described by three phases; firstly the limb swings backwards as a result of the propulsion, then muscle contractions allow for the limb to swing forward for locomotion, and lastly, the limb moves backwards and downwards, returning to the ground to be repeated or to remain in the stance phase, completing a stride. Each phase applies different forces on the limb's bone structure and musculature (Gillette and Angle, 2014).

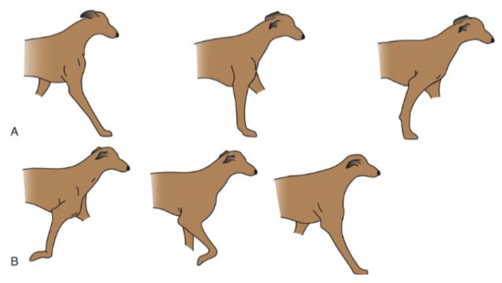

Fig. 1.2.1. Step cycle of the dog limb. A) Stance phase. B) Swing phase. (Gillette and Angle, 2014)

Alterations of stride length and frequency in these step cycle phases are carefully calculated when a dog selects its gait for the relevant locomotion needed. When observing dogs in optimal locomotion, it is noted that there are four main gaits used by dogs which are; walk, trot, canter, and gallop, with two transitional gaits; amble and pace. Variations in footfall patterns of the canter and gallop have led to additional descriptions of the gaits as rotary and transverse gaits. Each gait can be defined by a specific speed range with the walk being the slowest of the gaits and the gallop being the fastest and used as a sprint (M Christine Zink et al., 2018).

While dogs exhibit a variety of gaits for selecting an appropriate speed of locomotion, veterinary professionals typically focus on specific gaits that offer a good insight into a dog's functional capabilities (Table 1). The walk is a slow, four-beat gait that makes it helpful to visually assess each limb for gait abnormalities. The walking gait can be identified by observing how many limbs are in contact with the ground at the same time, as it is the only gait where 3 limbs will make contact with the ground. The footfall patterns of the walk follow a diagonal sequence, with a hind limb always starting locomotion, it is followed by the ipsilateral forelimb which is repeated by the opposite side. The trot is an efficient, ground-cover gait where the diagonal pairs of limbs move simultaneously to a two-beat footfall pattern which means that the forelimbs and hindlimbs never receive assistance from the opposite limbs to bear weight. For this reason the trot can be considered the best gait to use for detecting lameness. Additionally, the amble and pace are examples of transitional gaits which are very inefficient and are normally performed under specific conditions, such as fatigue or on difficult terrain which may provide insight into a dog's locomotor capabilities. Although the canter can provide insight into a dog's athletic capabilities, the canter and the gallop are not commonly used in gait analysis in veterinary rehabilitation due to their rapid and complex movements and therefore, excluded from the comparison on gaits (Table 1). Additionally, gait analysis of a walk and a trot generally offers an extensive understanding of a dog's locomotion (Gillette and Angle, 2014).

When investigating the relevant types of gaits specific for analysis in veterinary rehabilitation, they can be differentiated by variations in locomotory speed, changes in footfall patterns, and biomechanical features, which allows for the identification of the relevant gaits as detailed in Table 1; Locomotion speed increases from the walk to the trot with the amble being a transition gait. The forward movement and the footfall describes the order of the four limbs making contact with the ground in order to produce a forward movement of a selected gait and it can be noted that gait is initiated by a hind limb and the following limb placement will determine if a dog is in a trot on not, as the trot requires an alternating footfall pattern. Additionally, the biomechanical features are listed as key components of a gait, such as noting 3 placed limbs in a walk, or the ipsilateral limbs movement in an amble, and the trot being used for analysis.

Table 1. Comparison of canine gaits used in veterinary rehabilitation (Walk and trot) with a transitional gait (Amble)

GAIT	FORWARD MOVEMENT	FOOTFALL	BIOMECHANICAL FEATURES
Walk	1. One rear limb 2. Ipsilateral front limb 3. Other rear limb 4. Ipsilateral front limb	1. RR 2. RF 3. LR 4. LF	➔ 2 or 3 limbs are in contact with the ground at any given time ➔ Only gait in which 3 limbs will ever make contact with the ground at a given time
Amble	1. One rear limb 2. Quickly followed by ipsilateral front limb 3. Other rear limb 4. Quickly followed by ipsilateral front limb	1. RR 2. RF 3. LR 4. LF	➔ Appears as if ipsilateral limbs are moving together ➔ Faster form of the walk but not preferred ➔ Very inefficient: Rear end sways from side to side; rear limbs are not lifted very high; wasted horizontal energy ➔ Should only be used when transitioning from walk to trot
Trot	1. Two diagonal front and rear limbs 2. Moment where the body is suspended in the air 3. Other diagonal front and rear lim8bs	1. RF & LR 2. No ground contact 3. LF - RR	➔ Most efficient gait ➔ Opposite front and rear limbs must be able to support the body without help of the other limbs ➔ Often used in a gait analysis

LF = left front limb; LR = left rear limb; RF = right front limb; RR = right rear limb

The gait of a dog is made possible by the synergistic efforts of the skeletal structure and the neuromuscular systems. Conformation is a critical factor that affects how a dog's body moves and receives forces; it is the symmetry, size, and shape of various body segments relative to each other or in general appearance. Conformational abnormalities in body design predisposes a structure to injury due to uneven weight distribution causing additional strain on a particular body segment. Although locomotion varies for different breeds, a symmetrical gait should be performed during a gait analysis to reveal certain characteristics of a dog's conformation. A symmetrical gait describes the movements of one side of the body mirroring the movements of the other side, like the trot. In a trot, an asymmetrical gait should first be assessed for a conformational abnormality, which could be related to a structural fault and not that of pain compensation. However, incorrect movement can lead to musculoskeletal problems and if lameness is not a result of conformational abnormalities, other factors must be influencing the dog's locomotion, such as injury (Gillette and Angle, 2014). Knowledge of a dog's breed, body condition and unique conformation should guide the professional for expected gait abnormalities of an individual dog. Some breeds, such as Border Collies, sacrifice efficiency at the trot to excel at other aspects of performance with pelvic limbs that are adducted and internally rotated with externally rotated paws, commonly referred to as *cow hocks*, provide improved stability for lying down and standing up as well as turning capabilities.

In addition to anatomical factors such as bone conformations, joint health and neurological disorders, a dog's gait may be affected by physiological and environmental factors. Physiological factors such as age and body condition, as well as environmental factors of daily routine and housing, influence a dog's fitness and body condition. These intrinsic and extrinsic factors have a significant impact on a dog's gait and must be considered when evaluating a dog's gait and designing the rehabilitation plan to improve a dog's quality of life. It has been well documented that ageing dogs undergo slow deterioration of skeletal muscle mass, known as sarcopenia. This, coupled with neurogenic atrophy in many geriatric dogs, leads to decreased mobility and a reduced quality of gait. A poor body condition is commonly a result of a dog owner's misconception of appropriate nutritional requirements. Malnutrition, which affects gait due to muscle weakness, as well as overfeeding and a lack of exercise can have detrimental effects on a dog's gait if left untreated by increasing pressure on joints and muscles. Additional to the housing environment and a dog's daily activity levels, environmental factors of slippery or uneven terrain surface may affect the gait and comfortability of locomotion. Lastly, behavioural factors such as stress and fear can affect a dog's posture and movement pattern while pain will cause an altered gait to avoid discomfort (M Christine Zink et al., 2018). Through regular exercise and training, with the guidance of a veterinarian and a physiotherapist, a dog's muscle tone, flexibility and coordination can positively impact their gait leading to an improved quality of life.

Understanding dog locomotion enables trained professionals to be able to evaluate the conformation and gait of any dog through gait analysis, as it can be used diagnostically to determine causes and location of abnormalities or lameness, as well as to assess the rehabilitation of injuries for post-treatment patients. In competitive dogs it can be used as a tool to assess any subclinical factors that might affect performance (SportsVet, 2023).

2. Gait Analysis

Gait analysis is used in veterinary rehabilitation and physiotherapy as a comprehensive assessment of an animal's movement patterns. It involves a combination of visual observations and objective measurements. Performing a gait analysis enables a rehabilitation therapist to identify a dog's lameness or abnormalities which could have been caused by musculoskeletal or neurological conditions through qualitative comparison with normal locomotion or quantitative measurements. A gait analysis is part of an initial clinical assessment of a dog and is performed prior to specific orthopaedic or neurological evaluations in order to identify the affected limbs, and ensure a baseline understanding of the underlying conditions, such as muscle weakness, joint pain or neurological impairment (Carr and Dycus, 2016). The results of a comprehensive gait analysis guides the design of an appropriate individualised rehabilitation program for a patient's specific diagnosis. Additionally, it allows for the monitoring of a patient's progression and the evaluation of the rehabilitation program. A gait analysis is typically performed on a flat surface, although expanding the assessment to alternative terrain types, such as stairs and uneven surfaces could provide valuable insights (Koch et al., 2020). More often than not, a rehabilitation therapist is able to detect lameness in a dog's gait through observations from multiple angles at both a walking gait and a trot, while more subtle lameness may be difficult to detect. In recent years, more objective methods such as force plate and kinematic analyses have been developed to quantitate characteristics of a dog's gait enabling professionals to detect subtle lameness and more accurately measure gait parameters and a dog's response to various rehabilitation interventions (Carr and Dycus, 2016). While objective analysis methods have proven to be superior to visual observation in terms of quantifying gait parameters of the step cycle and range of motion, visual observation is effective, relatively easy to perform and cost effective, making it a practical tool in the clinical use of veterinary rehabilitation, and its importance should not be discounted.

The initial clinical assessment is composed of both subjective and objective assessments. Subjective assessments include the signalment and history of a dog which can provide crucial information about the medical background, ensuring that the appropriate treatment and contraindications are identified. A complete subjective assessment will include gathering information of a patient such as; breed, age and gender, neutered or intact, the owner's assessment of a dog's health and wellbeing, eating habits and diet, home environment and activity levels prior to and following the onset of a condition. Allergies, vaccinations and past medical history (disease, trauma and surgery), the history of the current condition (onset, duration, previous or current treatments), and the owner's impression of the progression of the condition should also be noted. Information from the owner is critical as they are the most familiar with the patient and their day-to-day wellbeing, while information regarding the formal diagnosis, surgical interventions, prescribed medications and possible complications should be gathered from the referring veterinarians along with any medical records, x-rays and blood tests. A subjective assessment should always be the starting point of a clinical assessment as it allows for the identification of clinical suspicions, possible predispositions and contraindications for certain therapies (Bockstahler et al., 2004). Following the subjective assessment, the posture and gait of a dog is assessed during an objective assessment. The patient should firstly be observed at rest in a stance and sitting position to evaluate weight distribution, the angle of the joints, the relationship between various body parts in relation to each other, as well as body shape and posture. Progressing with the assessment, an appropriate method of gait analysis should be selected according to the clinical context, depth of evaluation, resources and equipment available. The patient's gait can be assessed at both a walk and a trot to identify the affected limb, validate the information gathered during the subjective assessment, and gain insight into the nature and severity of the condition presented from the gait pattern. Regardless of the gait analysis method selected, it should be performed in an open but quiet space with minimal distractions as any changes to velocity and acceleration as well as any head turning will affect a dog's gait parameters (Koch et al., 2020). Following the objective assessment of the posture and gait of a dog, the clinical assessment concludes and further evaluations of orthopaedic functions are performed, such as specific palpation to assess muscle mass and tone, range of motion tests of the joints, specific body circumference measurements as well as testing neurological functions through various reflex responsiveness to ensure a comprehensive assessment of the patient. The results obtained from the subjective and objective assessment enables and guides an experienced rehabilitation therapist to design an appropriate rehabilitation program with optimal outcomes. Additionally, it determines whether any underlying conditions are contraindications for the use of certain treatment modalities (Prydie and Hewitt, 2015).

2.1. Visual Observation Analysis

Observations of a dog in standing and sitting positions provides an initial impression of their locomotor function by evaluating whether their weight is distributed cranially, caudally, or laterally to the left or right, as well as noting any internal or external rotation between the angle of the joints. Additionally, these observations provide insights into the position of various body parts in relation to each other which is important for the evaluation of the patient's body shape and posture. Therefore, it is important to ensure that the patient stands and sits squarely and as symmetrical as possible, looking forward with the head and neck relaxed in a neutral position to be able to observe their possible inabilities due to underlying conditions. It is recommended to choose an environment with minimal noise and distractions is important in ensuring that a dog under observation remains in its requested position (Koch et al., 2020).

Observing a dog at a stance enables a rehabilitation therapist to notice any unwillingness to bear weight on an affected limb which can be indicated by the placement of a paw in relation to the opposite paw as well as the digits being externally rotated (Figure 2.1.B). In severe cases, the patient may lift the paw from the ground and can be observed as completely or intermittently non-weight-bearing, although it is more common that the patient bears a moderate amount of weight on the limb when in the standing position. In addition to visually observing disparities of weight-bearing, the rehabilitation therapist may evaluate the level of weight bearing by placing their hands under both of the fore or hind paws of a dog to determine any lateral deviation. Computerised devices that simultaneously measure static weight bearing of all four limbs known as stance analysers are available and provide quantitative results of weight-bearing. An alternative quantitative approach that is reliable, simple and not as expensive as stance analysers can be achieved by having the patient stand with each limb individually on household scales to provide accurate and comparative results regarding static weight-bearing. In either case, the patient should undergo a period of acclimation to the therapist's manual manipulation as well as the scales to ensure accurate results and patient comfort (Millis and Levine, 2014). Along with a thorough assessment of any weight-bearing deviations, the flexion and extension of the joints at rest is observed, noting any hyperflexion or overextension of the joints which would affect the patient's posture (Figure 2.1.B). Similarly, the line of the patient's back at rest is assessed to determine any kyphotic or lordotic indications. Any observable weakness and trembling must be noted by the rehabilitation therapist including careful attention to the patient's head position and body conformation such as muscle asymmetry or swelling. Similarly, observation of a dog in a sitting position provides valuable insight into a dog's body conformation, joint movement and weight-bearing capabilities as well as lameness by noting any disparities from a symmetrical, square sit. The rehabilitation therapist should assess the patient's overall response to these positions and their ability of switching between a stance and a sit. In particular, comparing the patient's movement patterns with the functionally-correct movement patterns such as potential difficulties in pushing up from the hindlimbs to rise from a sit or difficulties in shifting their weight to their forelimbs to maintain a stance (Bockstahler et al., 2004). Observing a dog rising from a sitting or recumbent position may be useful as potential lameness or weakness will be more evident and severe immediately after rising and would improve with ambulation (Millis and Levine, 2014). Several example observational abnormalities of a dog's posture and their relevant interpretations include; A head in extended position indicates a relief of pressure on the hindlimbs. A hunched back could be an indicator for intervertebral disk disease or abdominal pain. The stifle joint being positioned under the body indicates pain on the extension of the joint. External rotation of the forelimbs could be indicative of an elbow or shoulder disorder, premature growth plate closure or asynchronous growth between the radius and ulna. Depressed digitigrade stance could be an indicator of a collagen defect, or ruptured plantar ligaments while a complete plantigrade stance would indicate a ruptured calcaneal tendon, tarsal trauma or an avulsion of the gastrocnemius. Abduction of the whole forelimb is a pressure-relieving stance and indicates an elbow or carpus disorder. Lateral deviation of the body centre indicates a disorder affecting the opposite side of the body. Low tail carriage could be indicative of a back disorder (Koch et al., 2020).

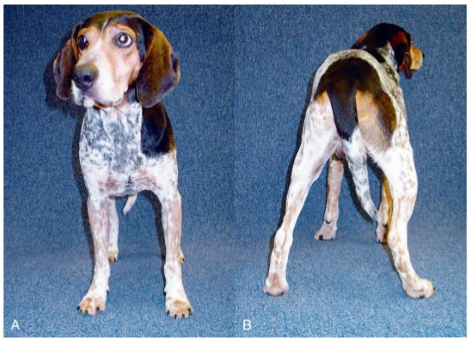

Fig. 2.1. Observation of a dog in a stance (A) from the front and (B) from the rear for evidence of reduced weight-bearing, asymmetry and joint hyperflexion or overextension. (Millis and Levine, 2014)

Visual Observation of a dog's gait is a commonly performed method of gait analysis due to its simplicity and cost-effectiveness for clinical use (M Christine Zink et al., 2018). A visual observation consists of evaluating a dog's quality of movement patterns at both a walk and a trot in a large open space and may be repeated on both even and uneven terrains as well as on stairs in order to target certain body parts and evaluate a condition's severity. A systematic and disciplined approach must be carried out to minimise potential subjectivity of visual observation that might arise from user-limitations such as human eyesight capabilities and human-errors due to inconsistent testing parameters (Carr and Dycus, 2016). Therefore, specific guidelines and an appropriate controlled environment along with correct documentation of results using standardised scales for grading lameness allows for a dog's gait to be evaluated in a semi-quantified approach through visual observation (M Christine Zink et al., 2018).

A dog's gait should first be evaluated on a flat surface with adequate traction before additional evaluations are performed on uneven terrains or stairs. For specific cases of performance or working dogs, the gait analysis may progress to evaluation of their gait in specific tasks such as jumping or running in a gallop (Carr and Dycus, 2016). In addition, a dog should wear a collar or harness with a loose leash to ensure the patient's comfort during their guidance through a gait observation. The gait analysis must be performed by observing the patient led by the client or an assistant from multiple angles including observations from behind, with the patient moving away from the rehabilitation therapist, from the front, with the patient moving towards the rehabilitation therapist, as well as from the side, with the patient moving across the rehabilitation therapist. This allows for the patient's hindlimbs to be observed and compared from behind, as well as the forelimbs from the front. The patient's stride length and consistency is observed from the side (Koch et al., 2020). The visual observation of a dog's gait is first assessed at a walk and then at a trot if the patient is able. Observing a dog's walk is beneficial as it allows for each limb to be evaluated independently and is especially useful for patients with severe lameness and unable to trot. Although the walk is the easiest to visibly note abnormalities as it is the slowest gait, subtle lameness may be more challenging to note through observations. Therefore, the trot is the best gait to use for detecting subtle lameness as it is the only gait in which the forelimbs and hindlimbs never receive assistance from the opposite limb in bearing weight (Millis and Levine, 2014). Abnormal proprioception such as ataxia, paw scuffing, or stumbling observed during the walk should be noted as potential indications of neurological disorders and may hinder the patient unable to trot or progress to more demanding locomotion along with severe lameness and pain indications that could be indicative of immobilizing orthopaedic conditions (Carr and Dycus, 2016).

Slow motion video recordings of a gait analysis is a beneficial tool that could be used in conjunction with the visual observations of a dog's gait to assist in identifying subtle lameness as well as being able to compare the original evaluation video with a patient's progress over time. Videos should be taken in as high resolution as possible at an ideal slow motion of 120 frames per second which allows for the evaluation of the patient's gait parameters to be carefully studied and discussed while being able to replay the video when needed as well allowing for accurate assessments of rehabilitation interventions through comparisons over time. The dog could be recorded during the visual observation from the perspective of the rehabilitation therapist performing the observations from multiple angles. The most informative angle would be recording the dog from the side view as there are multiple focal points of a dog's gait to evaluate during this observation such as relevant stride length, footfall patterns and joint angulations. Additionally, slow motion video recordings of a patient's trot is particularly helpful as it is a faster gait where critical information may be difficult to note using only visual observations (M Christine Zink et al., 2018).

A trained rehabilitation therapist with adequate experience and knowledge of the canine anatomical structures used for locomotion along with a good understanding of canine locomotion is able to evaluate a patient's relevant gait parameters such footfall patterns, stride length, frequency, step cycle phases and joint angles and their ranges of motion through a visual observation for detecting lameness or injury. Observations of pain or functional derangements will be presented by the affected limb spending less time in contact with the ground in comparison to the opposite limb to bearing less weight, this results in the affected limb presenting noticeably shorter strides and stance phases of the step cycles along with observations of reduced flexion and extension of an affected joint (Koch et al., 2020). Along with a lame limb circumduction during gait, lateral deviation may be observed by noting the paw of the affected limb placed further from the central body mass in an attempt to reduce weight-bearing. Increased lateral flexion of the vertebral column may be observed towards the side of the lameness in an attempt to assist the shortened step cycle which could be an indication of a hip or stifle condition (Millis and Levine, 2014). In forelimb lameness, a dog's weight is shifted caudally. This results in the observation of a dog's hindlimbs appearing tucked under the central body and the back appearing arched leading to shortened hindlimbs strides. Due to reduced range of motion, dogs with shoulder lameness tend to appear short strided, while dogs with an elbow lameness appear to circumduct the limb to ease pressure on the elbow joint. Alternatively, in hindlimb lameness, a dog's weight is shifted cranially, resulting in the forelimbs being placed more caudally, with the head and neck extended and lowered to reduce weight on the hind and maintain balance. An observed increased vertical motion of the hip on an affected side is labeled a "hip hike" as an attempt to reduce the limb's contact pressure with the ground along with the tail rising as the affected limb makes contact with the ground (M Christine Zink et al., 2018). Additionally, in the case of forelimb disorders, an upward nod of the head will be visible when the affected limb makes contact with the ground in an attempt to reduce weight-bearing. While, a downward nod of the head will be visible in the case of an affected hindlimb lameness to assist in shifting weight cranially. Observations of a similar grade of lameness on different types of terrains would suggest a lesion in the proximal half of the limb (from the stifle or elbow and upwards towards the axial skeleton) while lameness arising from structures of the distal limb, including the paw, carpus or tarsus, will be more pronounced on uneven terrains. Comparatively, distally located abnormalities often result in potentially non-weight bearing lameness due to the discomfort of ground-contact and a lack of support, while clinical signs resulting from proximal lesions tend to be less pronounced due to well-developed muscle mass surrounding the proximal joints which provides an a stabilising effect with obvious exceptions of severe pain (e.g. osteosarcoma) and neurological deficits (Koch et al., 2020). Interpretations of these noted gait abnormalities highlight the importance of evaluating symmetrical movement to identify affected limbs and specific indications of soft tissue injuries, orthopaedic conditions or neurological disorders.

Further visual evaluations of a dog's gait will be case specific and guided by the rehabilitation therapist's understanding of a patient's activity requirements and abilities to ensure the patient is not overexerted and pain is not provoked. An initial understanding of a patient's ability to use stairs is gathered prior to the evaluation to avoid potentially skewed results due to the patient warming up during ambulation of the gait analysis which could alleviate signs of lameness when evaluating their movement along stairs. During a gait observation on stairs, the patient's weight will be transferred to the front when descending the stairs, and to the back when ascending the stairs. Therefore, subtle lameness that is difficult to detect on even terrains may be more evident on stairs through observations of delayed contact with the ground or evidence of pain and discomfort. Additionally, the ability of a dog to jump over obstacles or into a car depends on normally functioning orthopaedic and neurological pathways between the limb and the caudal vertebrae. Generally, dogs are able to compensate for orthopaedic disorders distal to the stifle joint by transferring weight to the opposite side. Therefore, a patient's reluctance to jump or a reduced jump height could indicate that the hip, pelvis or vertebral column may be compromised or an indication of a potential neurological disorder. Due to the strenuous nature of a jumping evaluation, it should be avoided if the problem is obvious or the dog is in pain to ensure that further tissue damage is prevented (Koch et al., 2020).

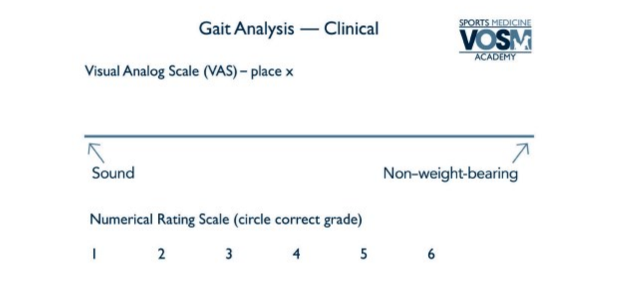

Fig. 2.1.2. Example of the Visual Analog Scale. The patient's gait is evaluated by placing an "X" along a linear scale where one side represents "sound" or normal uncompromised gait, while the other end represents "non-weight bearing" or a complete inability to place their own weight (Carr and Dycus, 2016).

To minimise complete subjectivity of the visual observation method of a gait analysis, results of a dog's walk and trot must be documented in a patient's medical record and can be semi-quantified by lameness grading systems such as a Numerical Grading Scale, which assigns a grading value to the severity of a dog's observable lameness. Similarly, a Visual Analog Scale (VAS) (Figure 2.1.2) is an alternative method of quantifying results of the visual observation gait analysis in which a dog's degree of lameness is marked along a linear scale. After the gait analysis and clinical assessment has been completed, the preferred and completed scale should be placed in the patient's medical record which allows for future comparisons to determine patient improvements, decline or stagnation (Carr and Dycus, 2016).

Table 2 is an example of a Numerical Rating Scale used to assign a lameness score to a patient after thorough observation. Grade 2 to 6 indicates lameness that can be observed at both a walk and trot. The grading system is standardised and ranges from normal gait (Grade 0) to completely non-weight-bearing (Grade 6) with slight increments of increased lameness, while each lameness grade description as well as the grade range may vary depending on the selected Numerical Grading Scale selected by a clinic. Weight-shifting refers to a compensatory weight distribution to alleviate weight from an affected limb. Weight-bearing lameness can be defined as a patient displaying willingness to use an affected limb which has reduced function. Non-weight-bearing lameness can be defined by an inability to support the body's weight due to excessive pain or loss of function which can be identified by intermittent ground contact or no contact at all (Koch et al., 2020).

Table 2. Example of a Numerical Rating Scale for Visual Observation of Gait (Carr and Dycus, 2016)

LAMENESS GRADE	DESCRIPTION
Grade 1	Uncompromised walk. Weight-shifting and subtle lameness during a trot
Grade 2	Subtle weight-bearing lameness
Grade 3	Weight-bearing lameness with distinct head displacement
Grade 4	Severe weight-bearing lameness
Grade 5	Intermittent "toe-touching" lameness
Grade 6	Completely non-weight-bearing lameness

In summary, performing a visual observation as a gait analysis method has proven to be very successful in evaluating a dog's quality of movement patterns and is a fundamental approach to identifying any deviations of healthy locomotion in order for diagnosing potential orthopaedic, neurologic or soft tissue injuries. The visual observation approach is simple to perform and requires minimal equipment which makes it ideal for clinical use in veterinary rehabilitation. It allows for immediate assessment of a patient's gait and provides good indications for the necessary rehabilitation interventions. Although a visual assessment allows for assessment of a patient's stride length, frequency and range of motion, it is heavily dependent on the observer's ability of interpretation and knowledge. A visual assessment aims at providing qualitative information while it may lack quantitative data of a patient's gait parameters such as ground reaction forces and precise measurements of joint angles and footfall patterns which requires advanced techniques and specialized equipment. The use of lameness grading systems and observation notes, results can be assessed and documented in a patient's medical record allowing for a rehabilitation therapist to determine realistic outcome measures for recovery and an estimated period of time necessary for rehabilitation interventions. While a visual observation may allow for potential subjectivity, its effectiveness at providing valuable insight into a dog's locomotion capabilities and identifying lameness through specific pathological indications highlights its importance in the rehabilitation of dogs.

2.2. Force Plate Analysis

While subjective gait analysis methods, such as visual observation, is often helpful in identifying lameness and evaluating the quality of a dog's movement, an objective gait analysis, such as force plate analysis, can be considered the golden standard for quantifying lameness and providing accurate data of a dog's gait parameters (M Christine Zink et al., 2018). A force plate analysis measures the relevant ground force reactions of a patient's stance phase during locomotion with metal force plates that are mounted into the floor along a walkway for the patient to move over (Figure 2.2.1) and allow for the evaluation of a dog's gait in clinical settings as well as for research on canine gait (Carr and Dycus, 2016). The force plate should be covered by a thin textured material such as a ground mat to ensure a dog maintains traction and comfort during passage over the force plate. The gait analysis can be performed using a single force plate or multiple may be placed in-line to create a longer site of analysis which enables the researcher to collect more data on multiple footfalls during a single pass of the dog (Kieves, 2022).

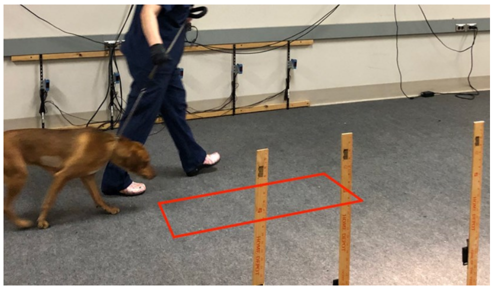

Fig. 2.2.1. Example setting of a force plate analysis. The force plate is mounted into the floor and outlined in red for demonstrative purposes (Kieves, 2022). The patient is guided by a handler over the force plate to measure specific gait parameters. Photo by Michael G. Conzemius

To ensure acceptable and accurate data collection, the gait analysis must be performed following a systematic and disciplined approach: Firstly ensuring that the environment is quiet and the patient will not be distracted, walk or trot the dog along the trial walkway by keeping the patient on a loose leash with the head looking forward during movement towards the center of the force plate. Start the trial at least 2 meters before the force plate to ensure that the patient is moving in a straight line, at a steady gait and a consistent velocity. Perform several practice trials before recording to acclimate the patient to the surrounding and the task required. Additionally, perform multiple data recording trials to ensure accurate and representative data is obtained by increasing the data set (Carr and Dycus, 2016).

The ground force reactions are assessed to determine indications of the distribution of the body mass over the fore and hindlimbs, speed and limb stiffness (Koch et al., 2020). The force plate measures forces in 3 dimensions (Figure 2.2.2); vertical (along the z-axis), craniocaudal (along the y-axis), and mediolateral (along the x-axis). The specific ground reaction forces measured by a force plate include; vertical forces such as, peak vertical force (PVF), vertical impulse (VI), and the rising and falling slope, anterior/posterior forces such as, propulsive force, propulsive impulse, braking force, braking impulse, as well as lateral/medial forces such as the mediolateral force. The relevant forces along each axis is measured during a force plate analysis and is automatically graphically recorded as a function of

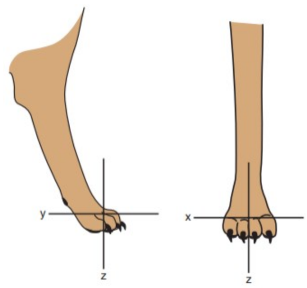

Fig. 2.2.2. Illustration of the 3 dimensional forces on a paw that is measured by a force plate. z-axis: vertical forces. y-axis: anterior/posterior forces. x-axis: mediolateral forces. (Millis and Levine, 2014)

force and time, with the maximum force generated along the relevant axis represented as the maximum value of the curve, while the relevant impulse force is represented as the area under the curve (M Christine Zink et al., 2018). Stride length and frequency can be evaluated by studying the timing of paw contact with a force plate. However, limited results may be recorded as a force plate analysis aims at investigating the forces exerted during a step cycle and, due to the size of a force plate, a complete gait with multiple strides may not be recorded.

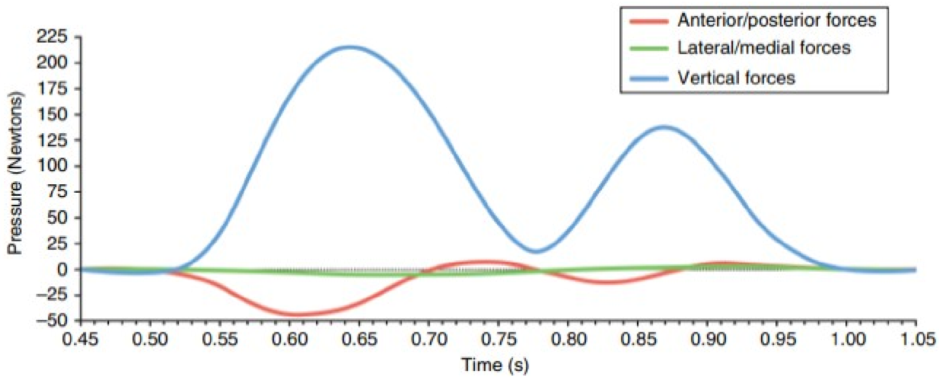

Fig. 2.2.3. Example of a typical force plate report **(M Christine Zink et al., 2018)**. Each dimensional force is represented by its own curve of force/pressure (Newtons) against time (seconds). The first recorded peak is produced by the placement of the forelimbs and the second peak by the hindlimbs.

Evaluating a force plate report (Figure 2.2.3), the peak vertical force (PVF) is defined as the single largest exerted force during an assessed dog's stance phase and it is recorded as a single data point on the force-time curve. The vertical impulse force (VI) is the assessment of a dog's push-off power which is derived by calculating the area under the vertical force curve and represents the force exerted by a paw onto the ground during the stance phase over a specific period of time. The PVF and VI values are evaluated to detect lameness as a lower PVF and VI will be noted in an affected limb. While the evaluation of the PVF and VI can be used clinically to provide an accurate lameness diagnosis, the braking, propulsion, and mediolateral forces provide a deeper insight into the mechanisms of a dog's locomotion and its relevant efficiency in terms of weight-bearing distribution and limb-loading patterns which can be studied to identify underlying causes of gait abnormalities, monitor the progression of diseases, and evaluate the effectiveness of treatment interventions following regular force plate analysis of a dog's gait (Carr and Dycus, 2016).

Canine locomotion requires proper functioning of the musculoskeletal system and coordination by the nervous system. Subjective gait analysis methods such as visual observation focuses on qualitative characteristics of a gait and limits the gait analysis to evaluation of the walk and trot due to the inability of the human eye to follow rapid movements, while a force plate analysis is an objective method of gait analysis which provides quantitative data for an accurate result-based assessment. The use of force plates in Veterinary medicine has become the most validated technology for the quantification of gait and therefore considered the optimum approach to thorough evaluation of gait parameters. Force plate analysis is a valuable approach for the clinical evaluation of patients with subtle lameness that may be undetectable through visual observations. However, a force plate analysis is more oftenly used in research to objectively assess the outcome of treatment interventions over time (Kieves, 2022). Although force plate analysis has been considered the golden standard for objectively evaluating gait parameters, limiting factors include; the inability to accurately measure stride length or frequency, the necessity for consistent velocity during multiple trials for accurate data, requiring a long dedicated walkway with costly specialized equipment which can be difficult to setting up and dismantling if needed, and comprehensive training for complex software and data analysis (Carr and Dycus, 2016).

2.3. Kinematic Gait Analysis

Kinematic gait analysis is an alternative objective method of gait analysis which is composed of attaching either colored, reflective, or LED, markers on a dog's specific anatomical landmarks, as seen in Figure 2.3.1 (B), to evaluate and quantify their positions, velocities, accelerations, and angles between joints and segments in relation to each other. The most common locations of marker placement can be seen in Figure 2.3.1. (A) and include the dorsal scapular spine, acromion/greater tubercle, lateral humeral epicondyle, ulnar styloid process, iliac crest, femoral greater trochanter, femorotibial joint, lateral malleolus of the distal tibia, and spinous process at T13 (M Christine Zink et al., 2018).

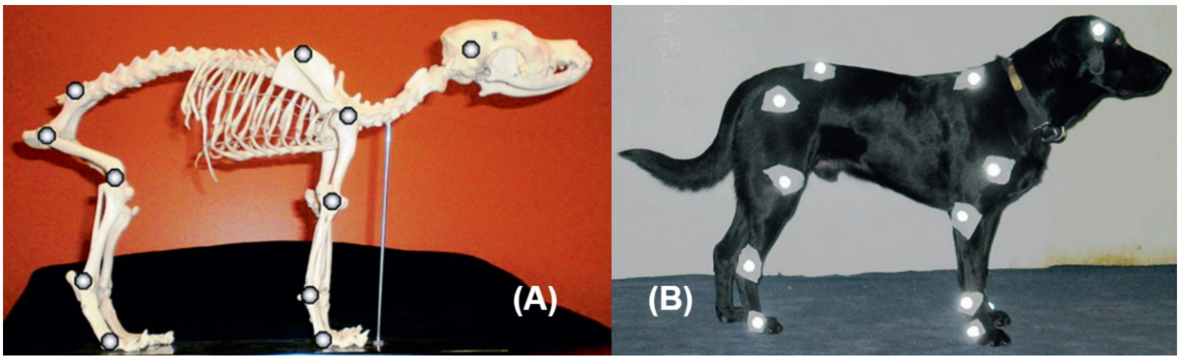

Fig. 2.3.1. (A) Visual representation of the anatomical landmarks used for marker placement during a kinematic analysis.**(B)** Example of correct reflective markers placement on a dog before the analysis. (Millis and Levine, 2014)

A clinician performing a kinematic gait analysis should decide on the relevant anatomical points necessary for the specific evaluation to be performed in order to prepare the marker attachment sites by shaving the fur and cleaning the skin with alcohol. The markers are attached directly to the skin with an adhesive back which might require further securing using tape to ensure that the markers do not fall off during gait (Carr and Dycus, 2016). The movement of the markers are tracked by a series of cameras which are assessed by a kinematic analytic system through different planes of space and time. The positional values obtained from the tracked markers are used to provide a quantitative gait analysis on the anatomical displacement by measuring the the distance a marker has moved, the linear or angular velocities and accelerations by calculating the speed and rate of anatomical change, as well as the range of motion by analysing the displacement pattern of a relevant joint. Additionally, using the cameras, the analytical software is able to create 2- or 3-D models (Figure 2.3.2) of a dog's gait with calculations of the relevant bone and joint movement obtained by the marker displacement (Millis and Levine, 2014).

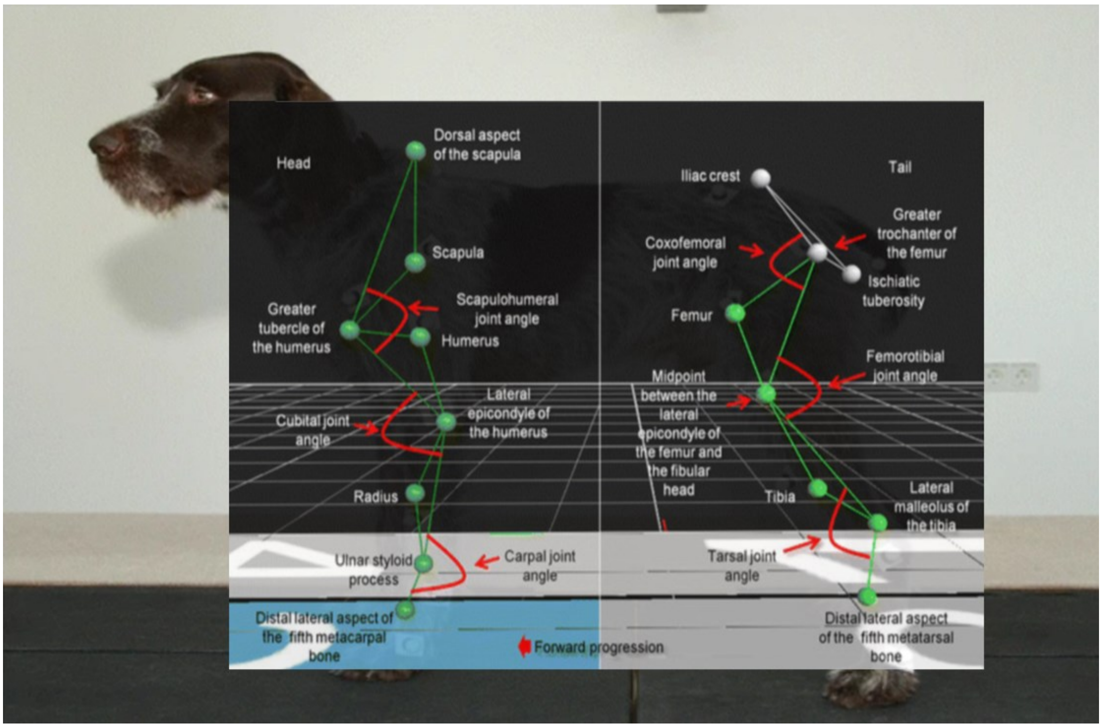

Fig. 2.3.2. Example of a recorded 2-D model of a dog at a stance overlayed over a photo of a dog. Illustration of the tracked markers on their anatomical landmarks are indicated by green and white spheres, and measured joint angles are represented by the curved red lines. (Galindo-Zamora et al., 2016)

In addition to the kinematic analysis system producing 2- or 3-D models to evaluate anatomical displacement, velocity, and acceleration, a dog's joint can be assessed with the tracked markers measuring the angle between the related bones as well as the range of motion which is recorded through graphical representation of the change in the joint angle during a step cycle (Figure 2.3.3) (M Christine Zink et al., 2018). A thorough analysis of the graphical data recorded for each tracked anatomical landmark a detailed kinematic understanding of a dog's joint angles, range of motion, stride length and frequency of the step cycle phases, and limb trajectories.

While valuable information can be gathered from a kinematic gait analysis, it is the most complex and demanding gait analysis method due highly-specialised, expensive equipment along with very extensive and time-consuming data analysis which makes it an inaccessible method of gait analysis for clinical use other than laboratory research. A major limitation of the method's practicality is the potential for skin movement due to canine skin

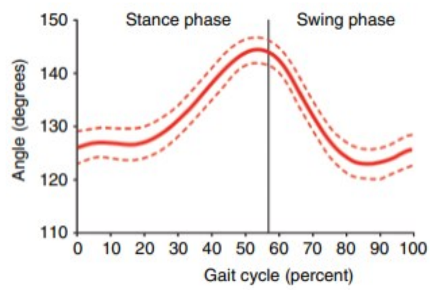

Fig. 2.3.3. Example of a kinematic report of the hip joint during a trot (recorded in the sagittal plane). The graph records the flexion and extension of the joint during a single step cycle to evaluate the relevant range of motion and its change through a step cycle. **(M Christine Zink et al., 2018)**

being considerably mobile, as well as difficulties of repeatability due to inaccuracies of marker placement. In comparative research, the variation of structures between breeds, as well as within breeds is an uncontrollable factor that negatively affects a study's results. Therefore, the kinematic gait analysis method is an ideal tool for researchers in the field of veterinary medicine and veterinary kinematics whose main responsibility is that of studying and comparing canine gait parameters with access to a laboratory with the specialised equipment necessary. Kinematic gait analysis provides valuable evaluation of a dog's lameness, however, can be considered greatly impractical for clinical use in veterinary rehabilitation.

In summary, selecting an appropriate gait analysis method depends on several factors. The most important being the purpose of the gait analysis. While gait analysis is used in research as well as in clinical use of veterinary rehabilitation, the clinical nature of a case aims at establishing the purpose of a gait analysis for rehabilitation use. Focusing on the clinical use of gait analysis, the purpose is determined on a case-by-case basis through the clinical assessment of patients seeking rehabilitation interventions. For patient's presenting mild lameness or common, well-studied conditions ranging from orthopaedic and soft tissue injuries to neurological disorders, a visual observation analysis can be considered the most suitable method as it will provide an experienced rehabilitation therapist or veterinary physiotherapist with the essential qualitative information necessary for designing a tailored rehabilitation program aimed at improving a patient's gait and therefore their quality of life. Patient's presenting more complex, misunderstood gait abnormalities and subtle lameness requires advanced techniques to evaluate their condition through quantitative measurements which will benefit from a gait analysis method which provides objective assessments such as force plate or kinematic analysis in order to proceed with rehabilitating the specific condition. Additional to purpose, the resources available to a rehabilitation therapist and practicality of a gait analysis method often determines the appropriate method of gait analysis as access to specialized equipment, such as force plates or kinematic analytic systems, is often not feasible unless considerate budgeting has been allocated for the necessary equipment, software and education of the relevant objective method. When considering the practicality of a gait analysis, time constraints of a method are relevant. A visual observation is simple to perform and results are obtained immediately which allows for a rehabilitation therapist to readily provide dog owners with comprehensive and realistic outcome measures based on the accessible rehabilitation interventions, while, kinematic analysis requires ample time for both the in-depth data collection and analysis. Additionally, the preparation of the patient with marker placement and set-up time of kinematic systems is very time consuming and results in undesired impracticalities for both the owner and for relevance of veterinary rehabilitation use. In many cases, combining multiple gait analysis methods may be beneficial in providing a comprehensive assessment of a patient's condition by using qualitative assessment for identifying gait abnormalities and quantitative evaluations for further investigation on a condition and monitoring its progression. Therefore, in conclusion, both subjective and objective gait analyses are important for establishing a diagnosis as well as for monitoring the progression of rehabilitation treatments. Therefore, by carefully considering relevant factors of each method, a rehabilitation therapist will be able to select the most appropriate approach.

3. **Rehabilitating Gait**

Rehabilitating a dog's gait is achieved following a thorough clinical assessment and physical evaluation to identify the source of a patient's pain and lameness, as well as assess the state of the involved tissues or structures, and determine the specific functional requirements and limitations of a dog. This information allows the rehabilitation therapist to develop an appropriate plan of care for a specific patient, including selection of treatment modalities and consideration of realistic outcome measures. Obtaining a patient's thorough subjective assessment (patient signalment and anamnesis), along with performing a comprehensive objective assessment (gait analysis and relevant physical evaluations), provides an understanding of the underlying condition, determining the implementation of certain rehabilitation interventions according to their therapeutic effects on the patient, as well as realizations of contraindications of certain modalities for the patient's diagnosis. The objective assessment of an in-depth gait analysis and relevant physical evaluations provide an insight into realistic expectations of outcome measures of rehabilitation interventions for a specific patient prognosis. Therefore, understanding the objective information collected during the physical evaluation, as well as patient-specific factors, and knowledge of biomechanics, the rehabilitation therapist is able to develop an effective rehabilitation plan to provide symptom free movement and optimal function aimed at returning a patient's activity capabilities to a realistic level of pre-injury function (M Christine Zink et al., 2018). Continued evaluation of a patient's progression and recovery is fundamental for successful rehabilitation as it allows for the assessment of the rehabilitation program and adaptation of the rehabilitation interventions to what works best for a particular patient (Bockstahler et al., 2004).

Although rehabilitation interventions have been well studied in dogs, the rehabilitation of similar conditions still differentiate between patients due to individual factors such as age, breed, and activity levels, as well as in severity, or progression of the underlying condition (Zink et al., 2018). However, by addressing a dog's condition early, rehabilitation therapists are able to counteract the impairment, injury, or disease, and accelerate the healing process for improved long-term outcomes before any secondary complications arise as a result of delayed intervention (Monk et al., 2006). Through communication with a referring veterinarian and careful consideration of a patient's contraindications, rehabilitation interventions should start as soon as possible to limit muscle atrophy, maintain joint range of motion, improve circulation, and prevent further recession of a patient's wellbeing. A rehabilitation program designed for a patient's specific needs, activity levels and medical history is crucial for an optimal recovery and realistic outcome measures, which should be monitored and evaluated as the patient progresses to ensure that the prescribed rehabilitation interventions remain efficient and appropriate (Millis and Levine, 2014). Therefore, by understanding the importance of early intervention and taking advantage of combining relevant therapeutic modalities, a rehabilitation therapist is able to optimize the rehabilitation process and help a dog return to a full and active life.
Early intervention of veterinary rehabilitation may result in several benefits including; a reduced severity of an underlying condition by limiting the extent of pain, muscle weakness, ligament ruptures, joint inflammation, or nerve degeneration, and accelerate recovery through stimulation of the body's natural

healing processes such as improved blood flow and cellular metabolism to prevent any secondary complications, such as muscle atrophy and joint stiffness, due to neglection of abnormal movement patterns. Therefore, by addressing issues early on, rehabilitation therapists can help dogs maintain their quality of life and mobility (Millis and Levine, 2014).

Veterinary rehabilitation consists of a wide variety of rehabilitation interventions, each with their own unique technique for targeted effects, indications, and contraindications of use. Based on the assessment findings, diagnosis and prognosis of a patient, a combination of treatment modalities will often be used to maximise outcomes and minimise the duration of recovery of optimal function (S Lindley et al., 2010). Each modality will need to be adapted to comply with the assessed patient-factors such as the severity of the underlying condition, and the realistic outcome measures of the rehabilitation. The practical use of different rehabilitation interventions in veterinary rehabilitation of dogs are described as manual, and physical therapy, hydrotherapy, and electrotherapy, being the most widely used treatment modalities due to their effectiveness in improving a patient's body condition through muscle strengthening, increased range of motion, improved fitness, and pain relief. Additional to these well used rehabilitation interventions, acupuncture can be prescribed for pain management and improved blood flow. While in severe cases of functional impairment, assistive devices, such as braces, splints, or wheelchairs, and assistive harnesses, are prescribed as an attempt to improve a dog's quality of life (Millis and Levine, 2014).

3.1. Manual Therapy

Manual therapy is the application of massaging techniques to provide essential therapeutic effects. As it is a well established human rehabilitation and physiotherapy intervention, its effectiveness has been studied and tested in animals and has been accepted as a treatment modality in veterinary rehabilitation. Massage has been proven effective in the alleviation of muscle tension and pain commonly caused by physical exertion. Various massage techniques are used to improve muscle efficiency and alleviate pain by locally increasing the blood flow which assists in improved oxygen supply and removal of lactic acid build up. In addition to its effectiveness for muscle tension and pain, massage may stimulate endorphin release which often results in a state of relaxation and enjoyment of the treatment (Bockstahler et al., 2004).

Indications for manual therapy are extensive as it can be applied to a variety of conditions that require the treatment of muscle pain and tension, commonly caused by physical overexertion, irregular gait, and stoic tendencies to an injury. Following trauma or surgery, early massage therapy may facilitate the healing process by limiting congestion of the affected area. Neurological patients may benefit from massage through improved muscle tone and sensory awareness. However, manual therapy is contraindicated for patients with local infection or inflammation of the skin, tumors, fever, bleeding disorders, or cardiac decompensation (Bockstahler et al., 2004).

While a vast variety of massage techniques are used in veterinary rehabilitation, a few of the most effective techniques include; Light, superficial tissue manipulation, called stroking, used to relax a patient in the beginning of a session or between deep massages. Kneading or skin rolling by gently grasping a layer of skin to roll in the direction of the muscle fiber which stretches and mobilizes the skin. Rubbing by creating gentle friction between both hands moving in alternating directions but along the muscle fibers to relieve tension. As well as applying circular pressure for the treatment of small, focal areas with moderate applied pressure in a circular motion to relieve tension (S Lindley et al., 2010).

3.2. Physical Therapy

Physical therapy is the systematic execution of therapeutic physical movements, postures, or activities that are planned in veterinary rehabilitation to stimulate a patient to exercise a recovering impairment as part of a final process of achieving optimal function (S Lindley et al., 2010). Therapeutic exercises are extensively used in physical rehabilitation programs as a non-invasive approach to manage a wide range of orthopaedic and neurological conditions, enhancing the general function of a patient to prevent long-term physical impairment, as well as a general improved fitness and wellbeing, optimising their health and reducing the risk of future injury (S Lindley et al., 2010). These beneficial effects are possible by achieving exercise goals such as, an improved pain-free range of motion and flexibility, a decreased lameness and increased limb usage, and increased muscle mass and strength (Bockstahler et al., 2004) as well as increased endurance, improved balance and proprioception (S Lindley et al., 2010). Therapeutic exercises can be prescribed for most patients, with very few exceptions, due the high adaptability of different exercise parameters for a patient's specific needs to allow for their optimal function.

In addition to an enhanced daily function, the different types of therapeutic exercises are responsible for their specific outcome measures; Passive exercises (Figure 3.3.1) which is composed of passive range of motion and stretching exercises, aims to improve the flexion and extension of a related joint as well as the flexibility of muscles, tendons, and ligaments through gentle application of a patient's comfortable range of motion (Bockstahler et al., 2004). Additionally, passive exercises enhance a patient's sensory awareness and proprioception by stimulating the sensory receptors in the skin and muscles which can be beneficial in relearning movement patterns (S Lindley et al., 2010). Assisted therapeutic exercises (Figure 3.3.2), composing of balance boards and swiss balls for assisted standing exercises, weight shifting exercises, and cervical mobility exercises. These exercises act as a bridge into active exercises for dogs which are recovering well from debilitating conditions such as neurological conditions or severe musculoskeletal trauma. Enhancing proprioceptive feedback, encouraging weight shifting and muscle contractions assists regaining a patient's ability to appropriately use their limb and facilitate balance (Bockstahler et al., 2004). Active therapeutic exercises (Figure 3.3.3), including slow walks, stair climbing, sit-to-stand exercises, jogging, wheelbarrowing, and cavaletti rails, are a few physical exercises that have been proven to help a patient improve their function through increased power and speed, while there are numerous additional active types of therapeutic exercises imaginable by a focusing on targeted muscle strengthening activities. For additional strengthening of a dog, more demanding active or resistance exercises (Figure 3.3.4) can be prescribed, such as ‘give-paw exercises’, pulling or carrying weights, short high speed runs, and controlled ball playing in the forms of interactive play exercises (Bockstahler et al., 2004).

Each patient participating in a rehabilitation program will need to progress through the different types of therapeutic exercises according to their current locomotion capabilities to ideally yield a complete recovery and optimal function. As a patient’s strength and coordination improves, they will be promoted from assisted exercise to active exercise, and onto resistance exercises, given that a diagnosis allows for a complete recovery. Alternatively, passive exercises are advisable for all patients, unless contraindicated for their condition, as they improve blood circulation and prepare tissues for more demanding active exercises. The rehabilitation therapist should monitor the patient during exercise and let them guide the progression and intensity of the exercises to ensure the patient is not overworked and pain is not elicited. Although therapeutic exercises are generally beneficial for rehabilitation, it should be avoided in the circumstances of; Acute or severe inflammation, unhealed fractures, infections, cardiorespiratory diseases, or severe pain (Bockstahler et al., 2004).

3.3. Hydrotherapy

Hydrotherapy can be defined as the use of exercise in water as a rehabilitation intervention where, depending on the hydrotherapy modalities available, the water is ideally heated to a comfortable temperature, which contributes to an overall increase in function, relaxation, and pain relief through improved blood flow, tissue elasticity, and cell metabolism. Hydrotherapy is determined by the properties of water and the basic principles that apply to an object interacting with water (S Lindley et al., 2010) which can serve as a highly efficient and effective veterinary rehabilitation modality. Specific principles of water that provide hydrotherapy its effectiveness is; Relative density, which determines the floating capabilities of a patient dependenting on their body fat composition. This results in a patient with a lower body fat content to sink faster than a patient with a higher body fat content if they remain motionless. Buoyancy, which is the upward force of water equal to the amount of water displaced depending on the relative submerged density, resulting in an immersed patient bearing less weight in water than on land. Therefore, water reduces the amount of strength a patient needs to support themselves and decreases the load on the limbs, allowing for more comfortable exercise of painful joints. Hydrostatic pressure refers to the depth of immersion as deeper immersion leads to greater pressure exerted on a patient which assists in reducing swelling and edemas. Water resistance, which refers to the additional force required for a patient to move through water, allows for muscle strengthening and cardiovascular training. Viscosity has a stabilizing effect, and together with buoyancy, allows for patients to stand in water, which were unable to successfully stand on land. Surface tension refers to the increased resistance at the surface compared to at depth and should be considered when rehabilitating weak and debilitated patients, as well as when needing to challenge a patient that is targeting strengthening, which can be controlled by adjusting the water level (Bockstahler et al., 2004). Hydrotherapy is a commonly prescribed rehabilitation intervention and it is indicated for the use in rehabilitation of patients following orthopaedic surgeries, such as fractures, cruciate ligament ruptures, and hip joint replacements, as well as for the use in rehabilitating patients following neurological injuries, such as intervertebral disk disease, and degenerative myelopathy. Additionally, it is commonly prescribed for use in muscle strengthening and improving joint function in patients with arthritis, spondylosis, and hip dysplasia (Bockstahler et al., 2004). Although using the properties of water for veterinary rehabilitation has great beneficial effects and outcome measures, careful exercise prescription must applied to patients, as the hydrostatic pressure of water will increase the pressure on the thorax and cause respiratory difficulties in patients with pulmonary conditions, and although warm water provides therapeutic effects, it could cause the overheating of a patient and increase cardiovascular stress if precautions are not taken. Specific contraindications of hydrotherapy include; heart and pulmonary diseases, open wounds, infectious skin diseases, and other infections (Bockstahler et al., 2004).

Hydrotherapy requires specific equipment installations (Figure 3.4.1), such as an underwater treadmill (UWT) or a pool, which are the most commonly recommended and performed forms of hydrotherapy interventions. These hydrotherapy modalities must be prepared for patient treatments with placement of non-slip mats, easy access into and out of the UWT as well as the pool with ramps, readily accessible drying equipment, and adequate water temperature and water quality, to ensure a safe and practical experience for the patient as well as the rehabilitation therapist (S Lindley et al., 2010). Comparing the use of a UWT or a pool as rehabilitation modalities, the UWT offers an ability to control the water level, inclination and to easily monitor a patient’s gait along the tread or in a swim with the use of mirrors or observations from the side of the tank, while a pool allows for a bigger area of exercise. Hydrotherapy exercises include perform standing exercises, involving the stabilizing and buoyancy effects of water to allow coordination training and gait retraining for neurological patients, walking exercises, using the buoyancy and resistance to strengthen muscles and improve gait patterns, as well as swimming exercises, to strengthen muscles and improve range of motion (Bockstahler et al., 2004).

3.4. Electrotherapy

Electrotherapy is a well-established rehabilitation intervention that can be classified as a group of therapeutic techniques which use electrical impulses to promote healing, reduce pain, and improve cellular responses through stimulation of the nerves and muscle cells. Electrical stimulation is a beneficial rehabilitation treatment for a wide range of orthopaedic conditions and neurological diseases that cause acute or chronic pain, as well as muscle atrophy. The relevant electrical stimulation modalities used in veterinary rehabilitation include Neuromuscular Electrical Stimulation (NMES) and Transcutaneous Electrical Nerve Stimulation (TENS) (Figure 3.2.1) which work by attaching electrodes to specific areas of a patient’s body with a conducting gel to stimulate the nerves and muscle cells, as well as modulate pain perception in patients (Bockstahler et al., 2004).

NMES aims primarily at improving muscle tone and muscle control through muscle re-education of direct stimulation, alongside pain relief. The electrical stimulation can be used to target specific muscles through low frequency electrical pulses, or larger muscle groups or tissues through higher frequency electrical pulses. Indications of NMES treatment include the acute or chronic pain management of musculoskeletal and neurological conditions, such as arthritis, spondylosis, nerve degeneration, and post-orthopaedic surgery. Additionally, NMES is indicated for use in combination with therapeutic exercises to prevent muscle atrophy, to strengthen muscles, to reduce muscle tension linked to overexercise, and promote fracture healing (treated surgically or conservatively) by inducing osteogenesis (S Lindley et al., 2010). NMES should not be used as a primary pain relief treatment of the underlying condition as it does not address the root cause of the pain (Bockstahler et al., 2004). Alternatively, TENS primarily aims to treat symptomatic pain by exciting sensory nerves that facilitates the pain-gate mechanism to block pain signals as well as causing the release of endorphins through electrical impulses. The mechanism of action is rapid, however, effective frequencies differ between patients and finding the most effective frequency can be challenging. Additionally, the pain-relief effect does not have a long lasting effect and pain signals will activate after the treatment has concluded (S Lindley et al., 2010). The use of TENS is indicated for both acute and chronic pain, while the site of electrode application will differ as segmental stimulation is preferred for acute conditions and local stimulation is preferred in chronic conditions (Bockstahler et al., 2004).

Electrical stimulation is contraindicated for application over or near to the patient's heart, eyes, or lower trunk. It should not be used on anesthetized areas of skin or sites of acute inflammation, as well as in the presence of tumors or infectious diseases. Ensure that a patient is not allergic to the electrode or gel, does not have any skin condition or haemorrhages. Additionally, it should not be used near the abdomen or pelvis in pregnant patients, over the growth plates in young patients, or for patients with implanted pacemakers (S Lindley et al., 2010). Electrical stimulation through NMES and TENS is a fundamental treatment intervention and commonly used in the rehabilitation of dogs. However, it is critical to have the knowledge on the correct use and careful considerations of the contraindications to safely and effectively apply its benefits.

Additional electrotherapy interventions include ultrasound therapy and laser therapy. Ultrasound and laser therapy are used to promote healing, reduce pain and reduce inflammation. Both treatments are able to penetrate tissues to act at the cellular level. Ultrasound therapy does this by generating high-frequency sound waves, while laser therapy provides its therapeutics through high-frequency light energy (S Lindley et al., 2010).

Laser therapy is a non-invasive electrotherapy modality which makes use of a laser to amplify and direct light energy. Although much of the applied light energy is absorbed by superficial tissue, it is able to exert its effects at a deeper level. Due to the penetrating effect of laser therapy, it triggers an enhanced cellular metabolism which assists in tissue growth and repair responses. Although the laser does not directly produce heat, the absorption of energy is converted into heat energy which assists in providing pain relief and an increased blood flow to reduce inflammation, as well as facilitating tissue repair with the laser's effects at a cellular level. While high-power laser therapy is able to penetrate deeper tissues, it poses a higher risk of tissue damage due to veterinary patients' relatively small body sizes. Therefore, low-level laser therapy is more commonly used in veterinary rehabilitation which has been proven effective, and is indicated for assisted wound healing, joint inflammation, soft tissue injuries and targeted pain relief (S Lindley et al., 2010). Similarly, ultrasound is a non-invasive modality involved in penetrating the skin, by producing high-frequency sound waves that reach the underlying tissue and generate heat to increase blood flow; promoting healing, reducing pain and reducing inflammation. The mechanical vibrations of the sound waves are above the human hearing range. They require a coupling medium between the transducer and the skin to ensure penetration of the skin. This may be achieved through direct coupling or indirect coupling. With the direct coupling technique, the transducer is placed directly on skin prepared with a coupling medium, such as ultrasound gel, which should be evenly spread over the site of treatment to ensure accurate transmission. However, this may cause practical difficulties in veterinary rehabilitation due to the treatment area needing to be shaved. Alternatively, indirect coupling techniques make use of submerging a target area in water and applying the transducer at 1 to 2 centimetres away from the target area allowing the sound waves to move through the water to treat the submerged area. Therefore, indirect coupling is useful for the treatment of small, irregular shaped body areas, such as the digits, carpal and tarsal joints, which would not have allowed for accurate direct coupling, although this technique can only be used if the patient is not afraid of water. Ultrasound is especially effective for the treatment of joint and muscle diseases, such as arthritis or spondylosis, by improving the elasticity of fibrous structures, increasing the blood flow, improving the tissue nutrition and relieving pain. The rehabilitation therapist must ensure proper use of ultrasound as incorrect use will lead to overheating of the tissues and possible cellular damage. Ultrasound treatment is contraindicated for tumors, infections, blood clots, and use over or around the heart, eyes, or the growth plates in young dogs (Bockstahler et al., 2004).

4. Animal Welfare in Veterinary Rehabilitation

Animal welfare is a critical consideration in veterinary rehabilitation clinics as it shares the common goal of improving the quality of a patient's life. Whilst rehabilitation interventions aim at ensuring the optimal physical capabilities and health of a patient, a high standard of animal welfare also ensures the mental and emotional well-being of a patient. By respecting key aspects of animal welfare in the context of gait analysis and rehabilitation, emphasizing ethical considerations in veterinary rehabilitation clinics and highlighting the importance of the human-animal bond, a holistic approach of comprehensive care can be achieved (S Lindley et al., 2010).

Gait analysis and rehabilitation procedures should always be performed with an attempt to minimise the stress and discomfort to ensure the mental well-being of a patient, which, in addition to animal welfare, directly contributes to the efficiency of rehabilitation through overcoming unwillingness and apprehension during treatment interventions. Stress can be minimised by providing a calm and welcoming environment without alarming distractions or potential conflicts. Additionally, the treatments should be performed gently and patiently, with positive reinforcement to encourage cooperation and to build trust with a patient. During rehabilitation intervention, exercises and treatments may be physically demanding, however, the rehabilitation program should be adapted to an individual patient's pain threshold and tolerance which should be thoroughly understood through careful assessments of gait and physical evaluations to avoid eliciting pain during treatment and handling. If a patient displays signs of discomfort, the current activity should be stopped or modified. Therefore, to ensure successful gait analysis and rehabilitation, a patient's overall well-being should be prioritized throughout the recovery process such as including adequate rest periods during a rehabilitation program, monitoring for signs of stress or discomfort, and adjusting the rehabilitation plan as needed (S Lindley et al., 2010). The human-animal bond plays a crucial role in the success of gait analysis and rehabilitation. A strong bond built on trust and understanding allows the animal to feel safe and secure throughout the process, facilitating cooperation and enhancing recovery. As a dog owner is the primary caregiver of a patient and understands their dog's day-to-day activities, their involvement in the rehabilitation process could yield more efficient treatments and a rapid recovery. An owner's patience, understanding, and active participation in the rehabilitation plan, can significantly improve the animal's well-being and recovery outcome measures (Bockstahler et al., 2004).

Additionally, a respectable veterinary rehabilitation clinic must follow the 5 Freedoms framework, established by prof. Robert Brambell, as a guideline on the core animal welfare standards for relations between patients and veterinary professionals. The 5 freedoms are an internationally recognized model for assessing animal welfare which outlines the fundamental freedoms that animals should have as:

1. Freedom from hunger and thirst
2. Freedom from discomfort
3. Freedom from pain, injury, and disease
4. Freedom to express normal behavior
5. Freedom from fear and distress

(Federation of Veterinarians of Europe, 2016)

In the context of gait analysis and rehabilitation, respecting these freedoms is critical and forms a part of defining veterinary rehabilitation. A gait analysis of a dog enables rehabilitation treatments to focus on alleviating pain, injury, and disease, while also ensuring the animal's comfort and ability to express normal behaviors and activities. The rehabilitation clinic and treatment modalities should be designed to minimize fear and stress, establishing a sense of safety and security. Additionally, good practices in veterinary rehabilitation facilitate a holistic approach that considers a patient's physical, mental, and emotional well-being. This is achieved through the early intervention of addressing gait abnormalities to prevent secondary complications and improve long-term outcomes. Individualized treatment plans are tailored to the specific needs of each patient, by considering their age, breed, activity level, and underlying condition. A multimodal approach of combining different rehabilitation techniques, such as physical therapy, hydrotherapy, and electrotherapy, can enhance the effectiveness of the treatment plan and allow for optimal outcome measures. Additionally, educating owners about the rehabilitation process, including home exercises and monitoring for signs of discomfort, will allow for a more efficient recovery. Therefore, animal welfare is an integral part of gait analysis and veterinary rehabilitation. By adhering to ethical considerations, building the human-animal bond, and implementing good practices, rehabilitation therapists can ensure both the physical and mental well-being of a dog during rehabilitation care. Improving a patient's physical condition while also enhancing its overall quality of life is a goal all veterinary rehabilitation clinics should pursue, allowing a dog to return to a happy and active life.

5. Conclusion

Gait analysis is fundamental to veterinary rehabilitation, providing a comprehensive evaluation of a dog's movement patterns to identify abnormalities and guide the development of targeted treatment plans. In addition to identifying lameness, gait analysis provides a comprehensive evaluation of a dog's locomotor capabilities, and allows for the development of a specialised rehabilitation program that optimizes recovery and improves the dog's quality of life.

A patient's diagnosis achieved from a gait analysis provides critical information on the indications and contraindications of implementing certain rehabilitation modalities. For instance, in manual therapy, gait analysis helps locate muscle tension or imbalances that need to be addressed through targeted massage techniques. In electrotherapy, such as NMES or TENS, gait analysis can identify specific muscle groups or nerves that require stimulation to alleviate pain or restore function. Similarly, in therapeutic exercises, gait analysis informs the design of exercise programs that focus on strengthening weakened muscles, improving joint range of motion, and restoring balance. In hydrotherapy, gait analysis can reveal subtle lameness or weight-bearing disparities that can be addressed through controlled underwater treadmill exercises.

Therefore, by understanding how a dog moves and compensates for injuries, rehabilitation therapists can use gait analysis to not only design more effective treatment plans but also to monitor the dog's progress over time, ensuring that the interventions are adapted to the dog's individual needs and recovery goals. Although gait analysis is a key component of veterinary rehabilitation, its application comes with limitations and challenges. A relevant challenge is the reliance on the expertise and knowledge of the rehabilitation therapist, particularly when using the visual observation method. The subjective baseline of this method can lead to inconsistencies in interpretations and limit the accuracy of quantifying gait parameters.

Force plate analysis, while considered the gold standard for objective gait analysis, requires specialized equipment and a dedicated environment, which may not be available in all clinical settings. Additionally, force plate analysis primarily focuses on the stance phase of the gait cycle, providing limited information on the swing phase and potentially missing crucial details about a dog's movement patterns. Kinematic gait analysis, which involves attaching markers to a dog's body and tracking their movement using cameras, offers a more detailed assessment of joint angles and range of motion. However, this method is time-consuming, requires highly specialized equipment, and is susceptible to inaccuracies due to skin movement and marker placement inconsistencies.

Furthermore, gait analysis methods may not always capture the full complexity of a dog's movement in its natural environment. Factors such as terrain variations, distractions, and the dog's emotional state can all influence gait patterns, potentially leading to skewed results. Overcoming these limitations requires a combination of careful observations, objective measurements, and a holistic understanding of the individual dog's condition and circumstances.

6. Bibliography

Amanat, Sonia, et al. "Canine Locomotion." *Encyclopaedia of Animal Cognition and Behaviour*, by Jennifer Vonk and Todd K. Shackelford, Springer International, 2020, pp. 1–6.

Bello, A, and HH Wamakko. "Comparative Anatomy of Selected Bones of Forelimb of Local Mongrelian Dog (Canis Lupus Familiaris) in Sokoto, Nigeria." *Insights in Veterinary Science*, vol. 5, no. 1, 14 Dec. 2021, pp. 026–031, https://doi.org/10.29328/journal.ivs.1001033.

Bockstahler, Barbara, et al. *Essential Facts of Physiotherapy in Dogs and Cats : Rehabilitation and Pain Management*. Babenhausen, Be Vet Verlag, 2004.

Boyd, Jacqueline. "Canine Morphology." *Encyclopaedia of Animal Cognition and Behaviour*, by Todd K. Shackelford and Jennifer Vonk, Springer International, 4 Sept. 2017.

Budras, Klaus-Dieter , et al. *Anatomy of the Dog:* 5th Edition ed., vol. 5th Revised Edition, Hannover, Schlutersehe, 2010.

Carr, Brittany Jean, and David L. Dycus. "Canine Gait Analysis." Mar. 2016.

Federation of Veterinarians of Europe. *Code of Good Veterinary Practice*. 4 Mar. 2016, web.archive.org/web/20160304065817/www.fve.org/news/publications/pdf/gvp.pdf.

Galindo-Zamora, Vladimir, et al. "Kinetic, Kinematic, Magnetic Resonance and Owner Evaluation of Dogs before and after the Amputation of a Hind Limb." *BMC Veterinary Research*, vol. 12, no. 1, 25 Jan. 2016, https://doi.org/10.1186/s12917-016-0644-5.

Gillette, Robert L., and T. Craig Angle. "Canine Locomotion Analysis." *Canine Rehabilitation and Physical Therapy*, by Darryl L. Millis and David Levine, 2nd Edition ed., Elsevier, 2014, pp. 201–210.

Guy, P. S., and D. H. Snow. "Skeletal Muscle Fibre Composition in the Dog and Its Relationship to Athletic Ability." *Research in Veterinary Science*, vol. 31, no. 2, 1 Sept. 1981, pp. 244–248, https://doi.org/10.1016/S0034-5288(18)32502-5.

Hermanson, John W, et al. *Miller and Evans' Anatomy of the Dog*. 5th Edition ed., St. Louis, Missouri, Elsevier, 2020.

Kieves, Nina R. "Objective Gait Analysis: Review and Clinical Applications." *Veterinary Clinics of North America: Small Animal Practice*, May 2022, https://doi.org/10.1016/j.cvsm.2022.03.009.

Koch, Daniel, et al. *Diagnosing Canine Lameness*. Stuttgart ; New York, Georg Thieme Verlag, 2020.

M Christine Zink, et al. *Canine Sports Medicine and Rehabilitation*. 2nd Edition ed., Hoboken, Wiley Blackwell, 2018.

Mcgowan, Catherine M, and Lesley Goff. *Animal Physiotherapy : Assessment, Treatment, and Rehabilitation of Animals*. 2nd ed., Chichester, West Sussex, John Wiley & Sons Inc, 2016.

Millis, Darryl L, and David Levine. *Canine Rehabilitation and Physical Therapy*. 2nd ed., St. Louis, Saunders, Cop, 2014.

Monk, Michelle L., et al. "Effects of Early Intensive Postoperative Physiotherapy on Limb Function after Tibial Plateau Leveling Osteotomy in Dogs with Deficiency of the Cranial Cruciate Ligament." *American Journal of Veterinary Research*, vol. 67, no. 3, Mar. 2006, pp. 529–536, avmajournals.avma.org/view/journals/ajvr/67/3/ajvr.67.3.529.xml, https://doi.org/10.2460/ajvr.67.3.529.

Prydie, David, and Isobel Hewitt. *Practical Physiotherapy for Small Animal Practice*. Chichester, West Sussex, Uk, Wiley Blackwell, 2015.

S Lindley, et al. *BSAVA Manual of Canine and Feline Rehabilitation, Supportive and Palliative Care : Case Studies in Patient Management*. Quedgeley, Gloucester, British Small Animal Veterinary Association, 2010.

SportsVet. "Basics of Locomotion & Gait Analysis of the Dog | SportsVet.com." *www.sportsvet.com*, 29 Dec. 2023, www.sportsvet.com/basics-of-locomotion-gait-analysis-of-the-dog/.

University of Calgary. "Dogs & Cats." *Faculty of Veterinary Medicine*, vet.ucalgary.ca/community/learning-animal-health/anatomy/dogs-cats.