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Ground Reaction Forces: The *Sine Qua Non* of Legged Locomotion

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Abstract

Legged locomotion results from the feet pressing against the ground to generate ground reaction forces (GRF) that are responsible for moving the body. By changing limb coordination patterns and muscle forces, the GRFs are adjusted to allow the horse to move in different gaits, speeds and directions with appropriate balance and self-carriage. This paper describes the typical GRF patterns in each gait, the adaptations that produce turning, and the GRF patterns used to unload the painful limb when the horse is lame. The intent is to provide information that is of practical interest and value to equine scientists rather than being a comprehensive review of the topic.

Keywords: horse; gaits; lameness; turning

1. **Introduction**

Locomotion is the act of moving through the environment. Regardless of whether this involves flying through air, swimming through water, or running over ground, the common denominator is the need to exert forces against the environment in order to initiate, maintain or change the movement. Sir Isaac Newton's Laws of Motion describe the relationship between the forces exerted by the body against the environment and the motion that results. These laws form the basis of classical mechanics. Briefly, the magnitude and direction of the forces exerted by the horse, through contact with the hoof and the ground, are balanced by a force of equal magnitude but acting against the hoof in the opposite direction. During locomotion therefore, as the hooves press against the ground during the stance phase, the ground pushes back against the hooves with a force of equal magnitude acting in the opposite direction (third law of motion) and this is called the ground reaction force (GRF). The magnitude and direction of the GRF determine the determine the amount and direction of the resulting acceleration of the body.

Force is a vector quantity which means that it is defined not only by its magnitude but also by the direction in which it acts. For example, applying a pulling force to an object versus applying an equal magnitude of pushing force to an object would produce a different force, as both would have the same magnitude, but they would be acting in different directions. Similar to other vectors, forces can be represented by an arrow that originate at the point of force application, are drawn in the direction that they act and are scaled in length to their magnitude. When representing GRFs during stance, the vector will originate from beneath the hoof, the arrow will be angled in the direction in which the force acts, and its length will be proportional in length to the magnitude of the force (Fig 1).

2. Stance Phase Kinematics

Ground reaction forces are generated when the hoof pushes against the ground in the stance phase of the stride and there is an intimate relationship between GRFs and limb kinematics. This section briefly reviews the relevant aspects of stance phase kinematics.

At initial ground contact the hoof is moving forward and downward. During the primary impact phase, which occupies approximately the first 50 milliseconds (1/20 second) after ground contact, the hoof is rapidly decelerated first in a vertical direction and then in a horizontal direction [1]. Due to the ratio between downward and forward movement of the hoof at contact, deceleration is higher in the vertical than the horizontal direction [2]. During trotting the fore hoof usually has a higher vertical velocity and lower horizontal velocity than the hind hoof at initial ground contact [3], which affects the relative vertical and longitudinal forces and may contribute to the higher incidence of concussive injuries in the forelimbs. Rapid hoof deceleration causes a shock wave to travel up the horse's limb. The high amplitude and rapid vibration frequency of the shock wave make it potentially damaging, particularly to the bones and joints [4]. During primary impact, the hoof is loaded by the relatively small mass of the digit, so forces remain low [1]. Deceleration and shock transmission associated with the primary impact increase with speed of locomotion, surface hardness and inability of the footing to damp the impact accelerations [1,5].

The proximal limb then descends and collides with the distal limb segments during the secondary impact. This phase is characterized by higher forces and lower decelerations compared with primary impact [1]. The forward motion of the body causes the hoof to slide over or plow through the surface before coming to rest [6]. Hoof sliding decreases the decelerative longitudinal forces at impact [5,7]. The distance and time over which hoof sliding occurs depends on the surface characteristics, including the speed of movement, the coefficient of friction between the hoof or shoe and the surface, and the depth of hoof penetration [8].

During the support phase, which occupies the period after secondary impact through midstance to heel lift, the limb is loaded by the horse's bodyweight. During the support phase, extension of the fetlock joint is associated with a stretch and recoil cycle in the superficial digital flexor tendon and suspensory ligament [9].

Heel lift marks the start of breakover when the hoof rotates around the toe in the final stages of propulsion [1]. On a hard surface, the hoof remains flat on the ground until heel off. On a softer surface the toe rotates into the surface, which affects loading of the distal limb structures [10].

3. Stance Phase Kinetics

3.1.Ground Reaction Forces

Ground reaction forces are generated throughout the stance phase. They are typically measured using a force plate [11-17] or forces shoes [18-21]. The vertical component can also be measured using an instrumented treadmill [22], calculated from whole body kinematics [23] or approximated using a pressure mat [24]. Artificial neural networks have been trained to determine GRFs based on strain profiles in the dorsal, lateral and medial hoof walls [25].

The three-dimensional GRF vector can be resolved into three perpendicular force components (Fig 1) to facilitate understanding the effects of the force. When the horse is viewed in the sagittal plane, the relevant force components act vertically and horizontally along the craniocaudal axis of the body. When the horse is viewed from in front or behind, the relevant force components act vertically and horizontally along the transverse body axis.

Each force component is typically plotted as a force-time graph (Fig 2) with the force measured in newtons (N) or kilonewtons (kN). The force values may be normalized to the horse's body mass and, in this case, the values are measured in N/kg or kN/kg. This simple procedure facilitates making comparisons between horses of different sizes and weights (Fig 3). The horse's body mass is 9.81 N/kg which is a useful reference point on normalized GRF traces. The time scale may also be normalized which makes it easier to compare the force curves for stance phases of different durations. Time normalization involves converting the stance time in seconds to a percentage of stance duration (Fig 4). It is informative to visualize both types of graphs to compare the forces generated over time, for example at different speeds. The force-time curves of different GRF components can be displayed on the same graph to visualize how their values co-vary over time.

3.2. Vertical GRF

The vertical GRF is designated positive in the upward direction. Its force-time curve may show some initial impact spiking, then the value rises rapidly to a double (walk) (Fig 5) or single (trot, pace, canter, gallop) (Figs 6 and 7) peak before declining to zero at lift off. The vertical force has the largest magnitude of the three GRF components; its peak value varies with body mass, limb, gait, and speed. In the forelimb maximal fetlock extension is proportional to the peak vertical GRF [26]. Heel lift is marked by a change in slope of the force curve in the later part of stance (Fig 1).

In the standing horse the forelimbs carry 58.6% of body weight compared with 41.4% in the hind limbs [27]. During locomotion, the force distribution varies through the stance phase in accordance with the sequencing and timing of limb contacts and overlaps. In trot, which is the gait that has been studied most extensively, the forelimbs generate approximately 58% of the vertical impulse in each stride, so there appears to be little change in load sharing between the fore and hind limbs.

Each gait has a characteristic limb support sequence that influences the distribution and summation patterns of the vertical GRF. When more than one limb is grounded, the total vertical GRF is the summation of the instantaneous force magnitudes of all weight-bearing limbs. The value changes through the stride oscillating above and below the value of the horse's body mass in a cyclic pattern that is repeated in successive strides. Note that when measuring the GRF of individual limbs, the mean vertical GRF generated by each limb may be less than the horse's bodyweight during much of the stance phase even during unipedal support (Fig 7).

3.3. Longitudinal GRF

The longitudinal GRF is considerably smaller in magnitude than the vertical GRF and the force-time curve has a very different shape. Most studies designate the positive direction as forward, and in this case the longitudinal GRF trace shows an initial negative phase during which it acts to decelerate or brake the forward velocity, followed by a positive phase during which it acts to accelerate (propel) the horse forward.

Impact spikes are a prominent feature in the longitudinal force trace in which they are more obvious than in the vertical GRF trace [28]. As the limb is loaded during the secondary impact phase, the frictional force increases and acts to decelerate the forward motion of the hoof. This results in a large impact spikes in the longitudinal GRF trace [2].

Useful variables describing the longitudinal GRF are peak braking and propulsive forces, time of zero longitudinal force (the transition from braking to propulsion) and the corresponding impulses. A change in slope of the curve in the later part of stance marks heel lift and the initiation of breakover (Fig 1).

In general, the forelimb has a higher peak braking force and a later transition from braking to propulsion compared with the hind limb, whereas the hind limb has a higher peak propulsive force and an earlier transition from braking to propulsion than the forelimb. As a result of these differences, the net longitudinal force is usually negative (braking) in the forelimbs and positive (propulsive) in the hind limbs [29]. Thus, the hind limbs are responsible for producing most of the propulsive force while the forelimbs control the speed. When the horse moves at constant speed on a level surface (steady state) the longitudinal impulse sums to zero over the entire stride.

The differences in longitudinal forces and impulses between the fore and hind limbs reflect the directional compliance of the limbs, as determined by direction of joint motion in the proximal limb joints (elbow, stifle). When the proximal joint points caudally, as in the equine elbow, the limb has a braking force bias, whereas when the proximal joint points cranially, as in the equine stifle, the limb has a propulsive force bias [30].

At any given time, the longitudinal forces of all concurrently-loaded limbs must be summed to determine the net effect in terms of braking or accelerating the horse's center of mass (COM). In addition to their role in speed control, the longitudinal forces are important in controlling the horse's balance and self-carriage [31].

3.4. Transverse GRF

The transverse GRF is small when traveling on a straight line. At walk, it is directed predominantly medially in the forelimbs and hind limbs [12] but in other gaits transverse forces show considerably more variability than the vertical and longitudinal components in both fore and hindlimbs [28,32].

3.5. Impulse

Impulse is the summation of the forces generated over a period of time, usually the entire stance phase. It is the area under the fore-time curve (Fig 2) and is calculated mathematically by integration of the force-time curve. Impulse also represents the change in momentum during the period over which it is measured. Impulse is determined both by the shape of the GRF curve and by the duration of the stance phase; therefore, two curves with different durations or different shapes can have the same impulse. Impulse is an important variable in determining the locomotor outcome of the hoof contacts with the ground. For example, during locomotion at constant speed on a level surface, the net longitudinal impulse per stride is zero and this can be achieved by various strategies that involve manipulating both the amplitude and timing of the force. During acceleration there is a net propulsive impulse and, conversely, during deceleration there is a net braking impulse.

3.6. Center of Pressure

The center of pressure (COP) is the point of application of the GRF beneath the sole of the hoof. It is sometimes called the point of zero moment. On a firm surface, the hoof is peripherally loaded, but on soft, deformable arena footing the entire sole surface of the hoof participates in load-bearing with a more equal force distribution between the toe and heel region and between the medial and the lateral sides especially at impact [33]. Regardless of the pressure distribution pattern, the COP represents the centroid of the forces beneath the hoof. The COP must be located correctly in order to accurately represent the location of the GRF vector relative to the limb. The COP path tracks the position of the COP for the duration of a stance phase (Fig 8). Many factors influence COP location and its final path during stance is likely to represent the outcome of a complex optimization process [34].

The COP is usually measured using a force platform or pressure mat [35] oriented in relation to the laboratory. As each hoof may land in a different orientation to the laboratory coordinates (e.g. toe in or toe out), and may slide on initial contact, measuring the location and orientation of the hoof when it lands will allow the COP data to be transformed to a hoof-based coordinate system. Using a hoof-based coordinate system therefore avoids introducing errors due to the hoof sliding and was reported to produce unique, highly repeatable COP patterns in individual limbs [34]. The COP path provides information describing the manner of hoof contact, the position of the COP through the duration of stance and the point of breakover. It does not indicate the speed of movement of the COP and it does not reflect differences in dorsal hoof wall angle. During trotting, the COP path for left and right forelimbs will not necessarily be a mirror image, however craniocaudal but not mediolateral patterns are highly correlated [34]. One study found that a majority of horses landed on the lateral side of the hoof and a majority landed dorsal to the center of the hoof [34]. Other studies have found a more palmar location of the COP at fore hoof landing with a dorsal progression throughout stance [36].

The position of the COP at midstance differs between studies. In newly-shod horses, van Heel et al. [37] reported that it was most often located in the mediodorsal quadrant in the front feet and in the laterodorsal quadrant in the hind feet. Eight weeks later, it showed a palmar shift in the fore hooves while the hind hooves developed an even greater preference for the laterodorsal quadrant. Barrey [36] described the COP as being close to the apex of the frog during most of stance. Nauwelaerts et al. [34] found that just over half the limbs had the COP under the lateral half of the fore hoof and in the majority of horses it was palmar to the center of the hoof. In late stance the COP moves toward the breakover point at the toe [36].

In a horse standing squarely pressure is concentrated on the medial quarters [38] with the COP located on the medial side. Interestingly, 6^{o} wedge shoes did not change COP position, while eggbar shoes were associated with a significant increase in the absolute distance from the toe to the COP [39]. These effects are believed to decrease the moment around the coffin joint and the pressure on the navicular bone.

3.7. Pedotti Diagrams

The magnitude, direction and point of application of the force vector change from one instant to the next throughout stance. Pedotti diagrams are a simple, temporo-spatial method of displaying and analyzing planar GRF vectors. The two-dimensional vectors for a complete stance phase are displayed at intervals, usually 1%, of the stride, in a single diagram (Fig 9). In this diagram, braking force vectors point to the left and propulsive force vectors point to the right.

Evaluation of Pedotti diagrams in the sagittal and frontal planes provide complete three-dimensional information for the vertical, longitudinal and transverse GRFs. The use of Pedotti diagrams in horses has been described [40] and applied to evaluate the effects of fore hoof unevenness [41]. If a line is drawn connecting the tips of the force vectors to form an envelope, a characteristic shape is evident for the fore and hind limbs in each gait. The envelope alone, called a vector dynamogram, has also been used [12,13] but this method lacks the additional information provided by the density of the vectors.

Visual evaluation of the Pedotti diagrams indicates the magnitude and orientation of the GRF vector throughout stance (Fig. 9). Comparisons are facilitated by overlaying the vector diagrams for different limbs or diagrams for the same limb under different conditions. A summary vector representing the magnitude (VecMag) and direction (VecAng) of the mean force over the entire stance phase can be calculated and superimposed on the force vector diagram. The values of VecMag and VecAng can be compared statistically. In addition, a technique called statistical parametric modelling has been described that compares the three-dimensional characteristics of the GRF curve through the entire stance phase [40].

4. Ground Reaction Forces in Different Gaits

Horses perform a repertoire of gaits that are characterized by having different limb coordination patterns. Typically, horses walk at slow speeds, trot at intermediate speeds and canter or gallop at fast speeds. Within each gait, the force-time graph has a characteristic shape in the fore and hind limbs [12-14,16,17]. In the symmetrical gaits, which include walk, trot, pace, and amble, the contralateral limbs have fairly symmetrical patterns on the left and right sides.

4.1. Walk

The walk is a 4-beat gait with limb placement sequence left hind, left fore, right hind, right fore. The limb support patterns alternate between having 2 or 3 limbs supporting the body. There is no suspension phase. Walk is classified as a symmetrical gait and symmetry of the kinematic and GRF variables has been confirmed biomechanically [42]. The contralateral (fore and hind) limb pairs overlap for periods of 10-12% of stride duration at the start of each stance phase. At this time one limb is retracted and exerts a propulsive force just before liftoff, the other is protracted and exerts a braking force as it accepts weight. After the retracted limb leaves the ground, the shoulders or croup vault over the grounded hoof.

Table 1 shows published values for the GRF peaks, their time of occurrence and the respective impulses in walk. The vertical GRF curve at walk is characterized by having two peaks separated by a dip (Fig. 5). The higher peak corresponds with the phase of the stride when the limb is closer to the horse’s COM; the second peak is higher in the forelimbs, the first peak is higher in the hind limbs [12,42,43]. Functionally, the peaks in the vertical GRF represent the role of the limb in controlling body movements. The first vertical GRF peak accelerates the body (shoulders or croup) upward in early fore/hind stance. The second peak occurs as the limb decelerates the descent of the body in late stance. At faster walking speeds, limb loading and unloading rates increase, limb contact times decrease, and the walk becomes more dynamic with higher peak forces separated by a deeper dip in midstance [44]. Kinematically, the peaks coincide with periods of bipedal support and the dips with periods of tripedal support [42].

Vertical GRFs are higher in the forelimbs throughout stance resulting in larger vertical impulses compared with the hind limbs [12]. Summation of all concurrent vertical GRFs (total vertical GRF shown by the pink line in Fig 5), oscillates around the horse’s bodyweight (9.81 N/kg). The value is approximately equal to bodyweight at hind contact, increases to a peak (~12 N/kg) at forelimb contact and decreases to a minimum just after forelimb contact (~7 N/kg) [42].

The longitudinal GRF traces show large impact spikes in early stance (Fig 5) that reflect longitudinal deceleration of the hoof. The magnitude and frequency of the impact spikes precludes showing a summation of concurrent forces. The longitudinal GRF traces for the walk show braking and propulsive phases in the fore and hind limbs (Fig 5). The transition from braking to propulsion occurs when the forelimb is oriented at or close to vertical, and in the hind limb when the hind hoof is vertically beneath the hip [12,45,46].

The timing of the longitudinal forces is such that at any time only one limb generates a braking force and one limb generates propulsion [42,43]. This coordination may be changed if the limb contact times differ from the ideal 25% of stride duration.

The transverse GRF is highly variable from stride to stride with left-right symmetry in the transverse GRF peaks being 85-88% [12].

Within-horse coefficients of variation for the peak force values are around 20% for the transverse GRF, 10% for the longitudinal GRF and 5% for the vertical GRF [12].

Walking velocity affects the GRF peaks and impulses. In the forelimbs, the vertical GRF peaks are higher, the dip between the peaks is lower, and the impulse is smaller at faster walking speeds [47]. This indicates that the increase in force magnitude is insufficient to compensate for the concomitant decrease in stance duration. Similar changes are seen for the vertical GRFs in the hind limbs in which the velocity-related differences are significant for the first vertical GRF peak and the subsequent dip [43].

4.2. Trot

The trot is an important gait for judging the quality of movement [48] and has long been regarded as the most relevant gait for lameness diagnosis [49]. It is a 2-beat, symmetrical gait with limb movements synchronized by diagonal pairs but usually with a brief dissociation of the footfalls and lift offs that has been related to trot quality [27,50,51]. A high-quality trot performed with the horse in uphill balance usually shows hind-first dissociation. By contrast, a horse that is on the forehand and in a downhill balance is more likely to show fore-first dissociation [50]. Hind-first dissociation is more energy efficient because the sequential limb contacts reduce collisional energy losses [52].

Table 1 shows published values for the GRF peaks, their time of occurrence and the respective impulses in trot. The vertical GRF graph in trot has a single peak (Fig. 6) that occurs a little before the temporal mid-point of the stance phase [27]. The peak value is higher in the forelimbs than the hind limbs. The ratio of fore:hind vertical impulse has been reported as: 56:44 for Dutch Warmbloods in hand [13], 57:43 for ponies in hand [11], and 57:43 in ridden dressage horses [27].

Breed-related differences have been reported with the generation of higher vertical GRFs and impulses projecting the horse into a more lofty suspension. This likely contributes to the significant differences reported in peak vertical force (as percentage body weight) for warmbloods (forelimbs 118%, hind limbs 96%) versus Quarter Horses (forelimbs 101%, hind limbs 92%) trotting in hand at the same speed [53]. In ridden dressage horses, Warmbloods also generate higher vertical impulses in the fore and hind limbs than Lusitanos in collected trot but not in passage, which is a highly cadenced type of collected trot [54].

The longitudinal GRF curve initially shows large impact spikes at the start of the braking phase and these are followed by a propulsive phase in both fore and hind limbs. The forelimbs have a larger peak braking GRF, a later transition from braking to propulsion, and a larger braking impulse than the hind limbs. Peak propulsive GRF is similar across limbs but the shorter duration of the propulsive phase results in a lower propulsive impulse in the forelimb than the hind limb [27].

The discrepancy in longitudinal forces between fore and hind limbs increases with the degree of collection and self-carriage [54]. Due to the discrepancy in the time of the transition from braking to propulsion in the fore and hind limbs, there is a period in the middle of stance when the sagittal plane GRF vectors converge with the braking forelimb vector oriented caudally and the propulsive hind limb vector oriented cranially. Convergence of the vectors is a strategy for improving balance.

The transverse component of the GRF is small in amplitude (<5% of the vertical GRF) and highly inconsistent [13]. It acts primarily in a medial direction in both the fore and hind limbs [13,55].

As trotting speed increases in the range of 2 to 5 m/s, stance duration and duty factor (stance duration expressed as percent body mass) decrease in all limbs and peak vertical GRF increases in the forelimbs but does not change in the hind limbs [11,56]. Impulse is distributed 57% forelimbs and 43% hind limbs regardless of speed [11,57]. Peak braking GRF increases with speed in both the fore- and hind limbs [56].

When a horse trots up an incline, the effect of gravity decreases the vertical GRF in the forelimbs and increases it in the hind limbs compared with trotting at the same speed on level ground. The impulse distribution is 52:48% on the fore:hind limbs on a 10% (5.7^{o}) incline. Peak vertical GRF is reduced in the forelimbs compared to level ground. Peak vertical GRF for the hindlimb is higher than that of the forelimb at speeds <3.0 m/s and, in contrast to level ground, hind limb peak vertical GRF increases with speed on an incline. Thus, moving on an incline results in the peak vertical GRF and impulses of the fore- and hind limbs becoming more similar with the impulse distribution changing to 52% forelimb vs 48% hind limbs. In the direction of motion, the braking GRF decrease in the forelimb and increase in the hindlimb and the propulsive GRF is greater for the hindlimb and less for the forelimb on an incline [11]. The impulse is larger for both limbs on the incline, with the forelimb creating a net braking and the hindlimb a net propulsive impulse. Longitudinal impulse summed over all limbs was slightly positive [11].

The trot is generally regarded as being a dynamically stable gait as a consequence of the diagonal limb support pattern. This support pattern provides a forelimb and a hind limb, respectively, cranial and caudal to the center of mass to stabilize pitching (uphill/downhill) rotations around the transverse body axis, together with a limb to the left and a limb to the right of the longitudinal body axis to provide stability against roll rotations. Horses adjust their pitch stability and control rotations around the transverse body axis, i.e. uphill/downhill balance, by redistributing the proportion of vertical impulse provided by the fore vs the hind limbs [57].

4.3. Tölt

Horses that have one or two copies of the DMRT3 gene perform ambling gaits in preference to trotting at intermediate locomotor speeds [58]. All ambling gaits are stepping gaits that have the same footfall sequence as walk without a suspension phase. They are distinguished from each other by inter-limb timing, rapidity of the footfalls, speed of progression and degree of animation. The tölt is an ambling gait performed, notably by Icelandic horses, at speeds ranging from <1 m/s to >6 m/s. The interval between successive footfalls should ideally be 25% stride duration.

The vertical GRF traces for tölt generally have a single force peak characteristic of a running gait. A double peak has been recorded in the hind limbs at slow tölting speed only (<2 m/s). In general peak vertical GRF and vertical impulse are higher in the forelimbs than the hind limbs. As speed increases, peak vertical GRF increases in both fore and hind limbs but forelimb vertical impulse decreases due to the shorter stance duration. The fore:hind vertical impulse distribution is 57:43 [59].

In the longitudinal direction, the forelimb produces a net braking impulse and the hind limb produces a net propulsive impulse at all tölting speeds. Peak propulsive GRF is similar in fore and hind limbs but the hind limbs produce significantly larger propulsive impulses at faster speeds [59].

The footfall pattern of tölt is the same as the walk but the GRFs are more similar to those of trot. Compared with trot, tölt has longer periods of overlap between the supporting limbs which lowers the peak vertical GRFs compared with trotting at the same speed. This may help to reduce the risk of overloading injuries and may be a factor in the ability of small Icelandic horses to carry relatively heavy riders.

4.4. Canter

The canter is an asymmetrical gait with synchronization of the movements of one diagonal pair of limbs. As the 3-beat footfall sequence progresses from hind to forelimbs, it is associated with a rocking motion of the body. The forehand is high when the hind limbs are grounded and low when the forelimbs are grounded. Each limb has a distinct and different function in terms of supporting the body weight, maintaining forward velocity, and controlling rotation around the center of mass. In accordance with these different roles and the inherent kinematic asymmetry, the GRFs differ, not only between fore and hind limbs, but also between the trailing and leading limbs (Fig 7, Table 2).

Table 2 shows published values for the GRF peaks, their time of occurrence and the respective impulses in canter. The vertical ground reaction force trace shows evidence of impact oscillations in early stance. Peak vertical GRF is smallest in the trailing hindlimb (approximately equal to body weight) and largest in the trailing forelimb (1.5 times body weight). Peak vertical GRF in the leading hind limb and leading forelimb are approximately 1.2 times body weight. The value for the summation of the vertical GRF is highest during the diagonal limb stance when the center of mass sinks to its lowest point during the stride [14].

The longitudinal ground reaction force in canter shows large impact oscillations in the first 20% of stance in all limbs. The force is predominantly propulsive in the trailing hindlimb as it acts to change the direction of movement of the center of mass from forward and downward to forward and horizontal. The leading hind limb contributes to both braking and propulsion and the trailing forelimb provides mostly forward propulsion. The leading forelimb exerts primarily a braking force as the horse is projected upward into the suspension phase [14,60].

The transverse GRF is very variable from stride-to-stride; Merkens and Schamhardt [14] did not find any consistent and meaningful results to report for this component.

4.5. Jumping

Jumping involves raising the horses center of mass high enough for all the body parts to clear the fence. The jumping effort is usually performed from a canter and the limb loading patterns, both at take-off and landing, are modifications of those described for cantering. When jumping a small fence of 0.8 to 1.0 m in height, the vertical GRFs are similar to those during cantering. Higher fences require larger vertical forces to raise the horse’s body in a higher trajectory but there are large differences between horses according to their inherent jumping ability. For example, Schamhardt et al. [61] showed that a horse with poor technique jumping a fence 0.8 m high generated similar GRFs to a horse with good technique jumping a fence 1.3 m high. Therefore, it is difficult to generalize across horses as to the vertical GRFs required to clear a fence with specific dimensions. Few data have been published for horses jumping large fences but in one horse the forces required to clear a 1.5 m fence were considerably larger than those required to clear a 1.3 m fence. The longitudinal GRFs show marked changes associated with redirecting the trajectory of the horse's body into the air at take-off then re-establishing forward motion after landing [61].

In the final approach stride the trailing forelimb initiates the elevation of the forehand by generating large vertical and braking GRF, followed by a large propulsive GRF [61]. The subsequent action of the hind limbs at take off applies large vertical and propulsive GRFs to project the horse's body over the fence. It also reverses the direction of trunk rotation from nose up to nose down so that the horse will land on the forelimbs.

The first limb to land is the trailing forelimb which has an almost vertical orientation at contact followed by a short duration stance phase. It is loaded vertically by the descending mass of the horse's body with a peak vertical GRF that is a little lower than the peak vertical GRF at take-off. This limb exerts a large propulsive GRF to move the horse forward away from the fence. Stance duration of the leading forelimb is considerably longer in duration than that of the trailing forelimb. It has a peak vertical GRF similar to take-off and exerts a large braking GRF. The trailing hind limb, which is the next to contact the ground, generates a large propulsive GRF that accelerates the horse forward and re-establishes the speed of the canter [61,62].

5. Effects of Lameness

Lame horses decrease structural stress by redistributing limb loading from the lame limb to the other (compensating) limbs [63-67]. Since forces are not visible to the human eye, detection of kinematic changes associated with unloading the painful limb form the basis of lameness detection and diagnosis. Visible signs include asymmetrical vertical excursions of the axial body segments (poll, withers, croup) and asymmetrical fetlock extension which is proportional to peak vertical GRF in that limb [26]. In horses with experimentally induced superficial digital flexor tendinitis, changes in vertical GRF in the lame and compensating forelimbs were reflected by changes in the angular excursions of the distal interphalangeal and metacarpophalangeal joints, whereas changes in longitudinal GRF were associated with alterations in limb protraction-retraction [64].

The H(orse)INDEX [68,69] software was developed to detect GRF asymmetries in contralateral limbs based on the amplitudes and timing of the force peaks in contralateral limb pairs. The subject was compared with a data bank of sound horses, ideally of the same breed, from which a *standard horse* was developed. Breed-related differences in vertical GRFs of horses with induced forelimb lameness was illustrated by Back et al. [53]: in Grade 2 lameness peak vertical forelimb forces were 89% bodyweight in warmbloods vs 78% bodyweight in Quarter Horses and in Grade 3 lameness the values were 69% bodyweight in warmbloods vs 66% bodyweight in Quarter Horses. Compared with the values when the horses were sound, the Warmbloods showed a relatively larger decrease in forelimb loading.

At the walk horses with an induced forelimb lameness have a short stance duration and reduced vertical GRF, particularly the second peak, in the lame limb. There is a compensatory increase in vertical force in the other three limbs, mainly the diagonal hind limb and contralateral forelimb. The propulsive phase is shortened so the lame forelimb contributes little to propulsion. The transverse GRF hardly changes [70].

The trot has long been recognized as the most important gait for lameness evaluation [49] based on its inherent symmetry and the fact that GRFs are higher than at walk. In trot a high vertical impulse produces a well-defined suspension phase indicative of orthopedic health. The first sign of mild lameness is often deterioration in trot quality because the horse avoids generating large vertical GRFs. Consequently, a mildly lame horse creeps rather than bounces over the ground. As lameness becomes more severe, the horse further reduces vertical GRF by rolling the weight forward over the lame limb onto the compensating diagonal. This avoids using the lame limb to raise the body [71].

A mildly lame horse chooses to reduce vertical GRF by trotting more slowly but, if forced to maintain trotting speed, stance duration increases so the necessary impulse can be generated over a longer time and with a lower peak vertical force [71]. In moderately severe lameness cases, vertical impulse is redistributed from the affected limb to the compensating limbs while maintaining total vertical impulse [66,67]. Forelimb lame horses most often shift weight to the diagonal hind limb during lame diagonal stance and to the contralateral forelimb during compensating diagonal stance [72].

6. Effects of Turning

During a lameness evaluation or a pre-purchase examination, a horse is typically evaluated moving on straight lines and on circles. In order to turn the body, the hooves must generate a turning or centripetal acceleration acting toward the center of the circle. The required centripetal acceleration increases on smaller radius turns and at faster speeds.

The easiest way for the horse to generate a centripetal acceleration is by leaning inward so the hooves push outward against the ground and the GRF is directed inwards. The frontal plane GRF vector is then somewhat aligned with the long axis of the limb. The forelimbs generate larger centripetal forces than the hindlimbs [73] and are primarily responsible for steering the horse. During turning the outside forelimb has a higher vertical GRF than the inside forelimb [74]. The outer hind limb also has a higher vertical GRF than the inside hind limb (Clayton, unpublished). These asymmetrical GRF patterns are associated with asymmetrical vertical excursions of the poll (head nod) and croup that simulate lameness of the inside forelimb and hind limb, respectively [75]. The degree of asymmetry increases with a reduction in circle diameter or an increase in the horse's speed. Therefore, it is important to standardize circle size and trotting speed when evaluating horses on the left and right reins on the longe.

The mechanical effects of circling tend to make a mild lameness appear more severe when the lame limb is on the inside of the circle and less severe when the lame limb is on the outside of the circle. Therefore, it is possible for a lame horse to appear sound when circling. Limb loading increases on the sitting diagonal when a horse is ridden at rising trot, so when on a circle, rising trot further decreases limb loading on the inside diagonal and increases limb loading on the outside diagonal. This may affect locomotor symmetry and the appearance of lameness [76]. It should be noted that certain types of lameness are exacerbated on the circle due to pain induced by a change in the limb loading pattern and this may over-ride the physiological effects of turning.

Declarations

No competing interests are declared.

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Figure Legends

Figure 1: Ground reaction force vector (grey) with its planar components. Left: sagittal plane view showing the vertical component (positive upward) and longitudinal component (positive forward); right: frontal plane view showing the vertical component (positive upward) and transverse component (positive medially).

Figure 2: Ground reaction forces and impulse. Left: vertical, longitudinal and transverse components of the ground reaction forces plotted against time for one stance phase of the left forelimb at trot. Arrow indicates impact spike in longitudinal force trace. Arrowheads indicate inflections marking heel lift in the vertical and longitudinal force traces. Right: vertical ground reaction force curve with vertical impulse shown as the shaded area.

Figure 3: Effect of mass normalization. The horse represented by the dark line weighs 514 kg and the horse represented by the light line weights 411 kg. Above: vertical force-time curve; below: mass normalized vertical force time curve.

Figure 4: Effect of time normalization. The dark curve represents the vertical force during the stance phase of a horse performing passage. The light curve represents the vertical force during the stance phase for the same horse performing collected trot. Note that passage has a considerably longer stance duration than collected trot. Above: vertical force-time curves; below: time-normalized (to stance duration) vertical force-time curves.

Figure 5: Sagittal plane force-time graphs for a horse ridden at collected walk. Vertical forces (above) and longitudinal forces (below) are shown for the left hind (dashed light line), left fore (solid light line), right hind (dashed dark line), and right fore (solid dark line). On the vertical force-time curve the horizontal line represents the combined weight of horse and rider and the pink line is the summation of vertical forces on all limbs.

Figure 6: Sagittal plane force-time graphs for a horse ridden at collected trot. Vertical forces (above) and longitudinal forces (below) are shown for the left hind (dashed light line), left fore (solid light line), right hind (dashed dark line), right fore (solid dark line) and force summation over all limbs (pink line). The horizontal line on the vertical force-time graph represents the combined weight of horse and rider.

Figure 7: Sagittal plane force-time graphs for a horse ridden at collected canter. Vertical forces (above) and longitudinal forces (below) are shown for the trailing hind (dashed light line), leading hind (dashed dark line), trailing fore (solid light line), and leading fore (solid dark line). On the vertical force-time curve the horizontal line represents the combined weight of horse and rider and the pink line is the summation of vertical forces on all limbs. Note that there is no suspension phase in this stride. Instead there is a period of overlap between the leading forelimb in the previous stride and the trailing hind limb in the stride shown.

Figure 8: Path of the center of pressure beneath the left fore hoof of a horse during one stance phase at trot. The colored dots represent the positions of markers on the distal hoof wall: pink on the lateral side (left), blue on the dorsal side (above), and green on the medial side (right). Hoof contact is close to the lateral marker and lift off is close to the dorsal marker.

Figure 9: Pedotti diagrams (upper row) for the four limbs during one stride at trot and summary force vector calculated over the entire stance phase (lower row). Braking is to the left, propulsion is to the right.

Table 1: Ground reaction forces in walk and trot. Walk data from Hodson et al., 2001, 2002. Trot data from Hobbs and Clayton, 2013.

Variable	Walk		Trot	
	Forelimb	Hind limb	Forelimb	Hind limb
First peak vertical force (N/kg)	4.45	4.02	10.52	8.81
Time of first peak vertical force (% stance)	18.6	20.6	45.4	43.2
Second peak vertical force (N/kg)	6.36	4.07	-	-
Time of second peak vertical force (% stance)	62.2	74.5	-	-
Vertical impulse (Ns/kg)	3.62	2.56	1.91	1.42
Peak braking force (N/kg)	-0.80	-0.82	-1.05	-0.74
Time of peak braking force (% stance)	19.3	14.9	29.1	23.1
Braking impulse (Ns/kg)	-0.21	-0.17	-0.11	-0.05
Peak propulsive force (N/kg)	0.92	0.74	1.02	1.09
Time of peak propulsive force (% stance)	77.6	79.1	72.9	62.7
Propulsive impulse (Ns/kg)	0.22	0.17	0.07	0.09
Time of zero longitudinal force (% stance)	51.8	45.9	53.0	37.9

Table 2: Ground reaction forces in canter. Data from Merkens et al., 1993. Signs for braking and propulsive forces have been changed so that braking forces and impulses are negative, propulsive forces and impulses are positive.

Variable	Trailing hind limb	Leading hind limb	Trailing forelimb	Leading forelimb
Peak vertical force (N/kg)	9.95	11.28	14.45	11.98
Time of peak vertical force (% stance)	18	46	45	49
Vertical impulse (Ns/kg)	1.31	1.55	2.01	1.61
Peak braking force (N/kg)	-0.86	-1.81	-1.35	-2.11
Time of peak braking force (% stance)	68	26	22	27
Braking impulse (Ns/kg)	-0.04	-0.13	-0.09	-0.20
Peak propulsive force (N/kg)	2.13	1.23	2.29	0.57
Time of peak propulsive force (% stance)	46	76	76	84
Propulsive impulse (Ns/kg)	0.18	0.07	0.16	0.03
Time of zero longitudinal force (% stance)	26	53	42	68