Der Einfluss diagnostischer Anästhesien auf das Fußungsmuster beim lahmen und lahmheitsfreien Pferd

INAUGURAL – DISSERTATION

zur Erlangung des Grades eines

Dr. med. vet.

beim Fachbereich Veterinärmedizin

der Justus-Liebig-Universität Gießen

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Aus der Klinik für Pferde (Chirurgie und Orthopädie) mit Lehrschmiede

Betreuer: Prof. Dr. M. Röcken

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Meinen Eltern

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Abkürzungsverzeichnis

AAEP	American Association of Equine Practitioners
COP	Center of pressure
CPG	Central pattern generator
GPS	Global Positioning Service
IMU	Inertial Measurement Unit
SD	Standardabweichung

1 Einleitung

1.1 Definition Lahmheit

Lahmheit ist eine Funktionsstörung des Bewegungsapparates, welche in der Bewegung oder bereits im Stand auffällig werden kann. Lahmheitsursachen können schmerzbedingt, mechanisch sowie neurogen bedingt sein (Baxter u. Stashak 2020). Die meisten Lahmheiten bei Pferden betreffen die Vordergliedmaßen, da diese mit ca. 60 – 65% des Körpergewichtes belastet werden (Baxter u. Stashak 2011). Zu 95% lässt sich die Lahmheitsursache an den Vordergliedmaßen distal des Karpus lokalisieren (Baxter u. Stashak 2011). Pferde weichen dem Schmerz aus, indem sie auf der betroffenen Gliedmaße während der Stützbeinphase weniger Last aufnehmen (Serra Braganca et al. 2021, Weishaupt et al. 2006). Durch eine veränderte Kopf- bzw. Kruppenbewegung wird die Gewichtsverlagerung zur kontralateralen oder diagonalen Gliedmaße erreicht (Weishaupt et al. 2006, Rhodin et al. 2018). Ebenso kann es zu Veränderungen des Vorführbogens sowie veränderten Gelenkwinkeln kommen (Weishaupt et al. 2008, Baxter u. Stashak 2020). Man unterscheidet im Rahmen der klinisch subjektiven Ganganalyse Stütz-, Hang- sowie gemischte Lahmheiten. Bei Lahmheiten an mehreren Gliedmaßen unterscheidet man primäre von kompensatorischen Lahmheiten (Baxter u. Stashak 2020). Der Bewegungsablauf lässt sich in die Stützbeinphase mit (Auf)fußen (Landen), Stützen, Stemmen (Abfußen) und Schwingen (Hangbeinphase, Vorführphase) unterteilen (Seiferle u. Frewein 1992).

1.2 Subjektive Lahmheitsuntersuchung

Die subjektive Lahmheitsuntersuchung erfolgt durch visuelle und akustische Beurteilung ohne technische Hilfsmittel. Vor und nach diagnostischer Anästhesie wird das Gangbild und der Lahmheitsgrad in der Regel mittels verschiedener etablierter Lahmheits-Scores beurteilt, die meist 5, seltener 10 Lahmheitsgrade umfassen (Edinger 2010, Dyson 2011). Das

Untersuchungsverfahren unterliegt einer subjektiven und somit fehleranfälligen Einschätzung (Arkell et al. 2006, Keegan et al. 2010, Dyson 2011, Fuller et al. 2006, Hewetson et al. 2006). Keegan et al. (2010) zeigten, dass bei einem AAEP-Lahmheits-Score > 1,5 die Übereinstimmung zwischen erfahrenen Pferdepraktikern bei der visuellen Beurteilung von Pferden mit Vorderhandlahmheit 94,2 % betrug, während die Übereinstimmung zwischen den Untersuchern bei Pferden mit einem AAEP-Score < 1,5 nur 65,8% betrug. Zudem weist die Beurteilung des Ausfalls diagnostischer Anästhesien markante Unterschiede zwischen den Untersuchern auf (Arkell et al. 2006). Ein Grund für die fehlende Übereinstimmung ist die begrenzte Sensitivität des menschlichen Auges (Näsänen et al. 2006, Keegan 2011).

1.3 Objektive Lahmheitsuntersuchung

Um das Ausmaß einer Bewegungsasymmetrie oder Gangstörung zu objektivieren und quantifizieren, wurden in den letzten zwei Jahrzehnten u.a. mehrere sensorbasierte Systeme entwickelt (Keegan et al. 2011, Reed et al. 2020, McCracken et al. 2012, Oosterlinck et al. 2010a, Oosterlinck et al. 2010b). Zur Lahmheitserkennung werden einerseits kinematische Bewegungsanalysesysteme auf Basis von inertialen Messeinheiten (Inertial Measurement Units, IMUs) herangezogen, die am Pferdekopf und Stamm angebracht werden, um die Symmetrie beziehungsweise Asymmetrie der vertikalen Kopf-, Widerrist- und Beckenbewegung im Trab zu erfassen (Keegan et al. 2011, Reed et al. 2020, McCracken et al. 2012, Marunova et al. 2021). Andererseits werden Kraft- und Druckmesssysteme verwendet, die auf der vergleichenden kinetischen Auswertung der Bodenreaktionskraft bzw. Druckverteilung von zwei benachbarten oder allen vier Gliedmaßen während der Stützbeinphase im Schritt oder Trab basieren (Oosterlinck et al. 2010a, Oosterlinck et al. 2010b).

1.3.1 Kinetische Untersuchungsverfahren

Kinetische Untersuchungsverfahren messen Bodenreaktionskräfte bzw. Drücke der Gliedmaßenspitzen auf den Untergrund. Dies kann durch stationäre Kraftmessplatten (force plates), Laufbänder mit integriertem Kraftmesssystem (instrumented treadmill), Kraftmess-Hufschuhe oder –eisen (force boots, force shoes) sowie Druckmessmatten (pressure mats), welche unter die Hufe geklebt werden, erfolgen (Keegan 2020). Schmerzen in der Stützbeinphase führen zu einer geringeren Lastaufnahme, wodurch die vertikale Kraft der betroffenen Gliedmaße vermindert wird (Weishaupt 2005, Weishaupt et al. 2006). Die Bodenreaktionskraft kann in vertikaler, sagittaler und transversaler Richtung gemessen werden, wobei eine verminderte vertikale Bodenreaktionskraft die größte Aussagekraft hinsichtlich des Bestehens einer Lahmheit hat (Keegan 2020). Das Auslösen einer undeutlich geringgradigen, geringgradigen sowie mittelgradigen Lahmheit mindert die vertikale Bodenreaktionskraft um 4%, 9% bzw. 24 % (Weishaupt 2005), das Auslösen einer Lahmheit vom AAEP Grad 4 sorgt für eine Reduktion um 50% (Keegan 2020).

1.3.1.1 Hoof™ System (Fa. TekScan, Boston, USA)

Das Hoof™ System gehört zu den Druckmessmatten und kann zur Messung der vertikalen Kraft (in N) beziehungsweise des vertikalen Drucks (in kg) sowie des Druckmittelpunktes unter den Pferdehufen eingesetzt werden (Hagen et al. 2016, Al Naem et al. 2020, Al Naem et al. 2021, Buser et al. 2023). Die 0,15 mm dünnen Sensorfolien (Hoof Sensors Modell #3200E, Tekscan, Inc., South Boston, USA) des Systems erfassen die vertikale Kraft mit einer räumlichen Auflösung von 3,9 Sensorzellen/cm² und einer Aufzeichnungsfrequenz von 250 Hz. Die Sensorfolien werden unter beiden Vorderhufen mittels Klebeband fixiert, wodurch das System mobil und auf unterschiedlichen Bodenbeschaffenheiten verwendet werden kann (Hüppler et al. 2015). Das Gerät wird vor jeder Messung gemäß den Anweisungen des jeweiligen Herstellers sowie früheren Veröffentlichungen kalibriert (Lange et al. 2012, Perino et al. 2007). Eine Validierung des Systems anhand eines Goldstandards hat in der Veterinärmedizin noch nicht stattgefunden, allerdings wurde das Gerät bereits in verschiedenen klinischen Studien verwendet (Lange et al. 2012, Fürst et al. 2016, Hagen et al. 2016, Al Naem et al. 2021, Buser et al. 2023).

1.3.2 Kinematische Untersuchungsverfahren

Die Kinematik beschäftigt sich mit Asymmetrien im Bewegungsablauf, welche beispielsweise durch Schmerzen in einer Körperhälfte hervorgerufen und somit mit Lahmheit assoziiert werden können (Keegan 2020), auch wenn die Abgrenzung zwischen einer klinisch relevanten und einer nicht beeinträchtigenden Bewegungsasymmetrie geringen Ausmaßes im Einzelfall nicht immer sicher möglich ist (Mecaire et al. 2022). Zur Erkennung von Lahmheiten der Vorder- und Hintergliedmaßen können Lageveränderungen verschiedener anatomischer Landmarken herangezogen werden: So können die Asymmetrie der Kopf- und Kruppenbewegung (McCracken et al. 2012), Dauer der Stütz-und Hangbeinphase (Weishaupt et al. 2006), das Rückziehen der Gliedmaße, Gelenkwinkel (Fesselstreckwinkel) und Vorführgeschwindigkeit (Serra Braganca et al. 2021) ermittelt werden.

1.3.2.1 Lameness Locator® Equinosis®

Der Lameness Locator®, bestehend aus Hardware (Q®) und Software (Lameness Locator®), dient der objektiven kinematischen Lahmheitsuntersuchung (Keegan et al. 2011). Mit Hilfe von inertialen Messeinheiten (Inertial Measurement Units, IMUs), die auf Genick, *Tubera sacralia* sowie an der rechten Vordergliedmaße platziert werden, wird die vertikale Verlagerung von Kopf und Becken sowie die Winkelgeschwindigkeit der rechten Vordergliedmaße im Trab gemessen (Keegan 2020). Die Daten werden per Bluetooth an einen Tablet-Computer übertragen. Die Sensordaten (Beschleunigung) werden algorithmisch umgewandelt, um im Trab die vertikale Position relativ zum Boden (Keegan 2020) und Asymmetrien in der Kopf- und Beckenposition zwischen linker und rechter Körperhälfte zu bestimmen: Die mittlere Differenz in mm der maximalen (HDMax) sowie minimalen (HDMin)

Kopf- bzw. Beckenhöhe (Grenzwert Vorderhandlahmheit: +/-6 mm, Grenzwert Hinterhandlahmheit: +/-3 mm). Die Auswertung zeigt, welche Gliedmaße von Lahmheit betroffen ist und in welcher Bewegungsphase die Asymmetrie auftritt: Auffußen (impact) und / oder Abstemmen (pushoff). Die nummerischen Ergebnisse werden geclustert und als geringgradig, gering- bis mittelgradig, mittelgradig, mittel- bis hochgradig, hochgradig interpretiert. Anhand der Standardabweichung (SD) des Mittelwerts der gemessenen Asymmetrien wird angegeben, wie verlässlich die Aussage ist (gering-, mittel- bzw. hochgradig) (Ros 2021, Equinosis 2016).

1.4 Diagnostische Anästhesien

Als Goldstandard zur Schmerzlokalisierung dienen diagnostische Anästhesien, sofern klinisch keine ausreichenden Hinweise auf die Lahmheitsursache vorliegen (Schumacher et al. 2013, Baxter 2020). Akute Lahmheiten, deren Ursache unvollständige oder vollständige Frakturen oder Sehnenläsionen oder septische Prozesse sein können, gelten ohne vorherige Abklärung als Kontraindikation, in diesem Fall sollte eine röntgenologische bzw. ultrasonografische Untersuchung vorgezogen werden. Auch entzündliche Reaktionen (z.B. Mauke, Dermatitis, Verletzung) im Bereich der Injektionsstelle des Lokalanästhetikums können die Wirksamkeit und somit das Ergebnis der diagnostischen Anästhesien beeinflussen (Edinger 2010). Man unterscheidet Leitungsanästhesien (lokale Nervenanästhesie), intrasynoviale Anästhesien sowie Infiltrationsanästhesien. Erstere werden von distal nach proximal durchgeführt, um die schmerzhafte Region einzugrenzen. Letztere sind gezielte Anästhesien, welche im eingegrenzten Gebiet durchgeführt werden und nicht in einer bestimmten Reihenfolge durchgeführt werden müssen (Baxter 2020).

1.4.1 Lokalanästhetika

Die zur Lahmheitsuntersuchung verwendeten Lokalanästhetika umfassen zumeist Lidocain, Mepivacain und Bupivacain. Diese zum Amid-Typ gehörenden Lokalanästhetika unterscheiden sich in Wirkungseintritt und –dauer (Richter 2010). Lidocainhydrochlorid 2% und Mepivacainhydrochlorid 2% haben einen schnellen Wirkungseintritt. Da Mepivacain jedoch länger wirksam (mehr als 2 Stunden im Gegensatz zu 60 Minuten bei Lidocainhydrochlorid) und weniger gewebereizend ist, wird es häufiger verwendet (Baxter 2020, Bidwell et al. 2004, Hoerdemann et al. 2017). Die Wirksamkeit von Bupivacainhydrochlorid tritt langsamer ein, hält jedoch 4-6 Stunden an (Baxter 2020). Es wird hauptsächlich für therapeutische und weniger für diagnostische Anästhesien angewendet (Bassage u. Ross 2011).

1.5 Druckmittelpunkt (center of pressure, COP) und Druckmittelpunkt-Pfad

Der Druckmittelpunkt beschreibt den zentralen Druckpunkt aller Kräfte und Drehmomente, die während der Stützbeinphase auf den Huf übertragen werden (Buser et al. 2023) und kann mit Druckmesssystemen ermittelt werden (van Heel et al. 2004, Oosterlinck et al. 2013). Der COP-Pfad ist die Verschiebung des Druckmittelpunktes während der Stützbeinphase vom Auf- bis zum Abfußen (Buser et al. 2023), der für jedes Pferd und jede Gliedmaße individuell ist (Nauwelaerts et al. 2017). Der Verlauf des COP-Pfades eines Pferdes wird durch zahlreiche Faktoren beeinflusst, wie Körperbau, Kinematik des Rumpfes und der Gliedmaßen, die Interaktion zwischen Huf und Boden, sowie neuromuskulären Komponenten (Hagen et al. 2017, Nauwelearts et al. 2017). Im Gegensatz zur Ermittlung von Bodenreaktionskräften sind die Ermittlung des Druckmittelpunktes und COP-Pfades im Rahmen objektiver Lahmheitsuntersuchungen noch relativ unerforscht, obwohl schon früh die Bedeutung der Druckverteilung bei der Beurteilung von Lahmheiten vermutet wurde (Seeherman et al. 1987) und bereits Unterschiede des COP-Pfades zwischen gesunden und Pferden mit Strahlbeinerkrankungen festgestellt werden konnten (Wilson et al. 2001). Buser et al. (2023) konnten zeigen, dass sich der COP-Pfad auch bei unilateral chronisch lahmen Pferden sowohl an der lahmen als auch an der lahmheitsfreien Gliedmaße in hohem Maße wiederholt und für jedes Pferd und jede Gliedmaße charakteristisch ist. Außerdem scheint die Variabilität des COP-Pfades an der lahmen Gliedmaße im Vergleich zur lahmheitsfreien Gliedmaße verringert (Buser et al. 2023). Des Weiteren konnte der Einfluss unterschiedlicher Hufeisen auf den Druckmittelpunkt ermittelt werden (Hagen et al. 2016, van Heel et al. 2005).

1.6 Fortbewegung

Das Muster der Fortbewegung wird von zwei interagierenden Komponenten beeinflusst - dem CPG (central pattern generator) im Gehirn und Rückenmark und der peripheren Propriozeption (Guertin 2012). Hirnstammareale erzeugen hierbei neuronale Signale, welche an Zentren im Rückenmark weitergeleitet werden. Diese sind für das Zusammenspiel der Beuger- und Streckmuskulatur sowie der Koordination zwischen den Gliedmaßen zuständig. Periphere Propriozeption modifiziert die zentral erzeugten Bewegungen für einen reibungslosen und koordinierten Bewegungsablauf (Bowker et al. 1995). Entgegen der Annahme, dass propriozeptive Reflexe den ersten Bodenkontakt des Hufes zu Beginn der Stützbeinphase beeinflussen (Clayton 1990), konnten mehrere Autoren zeigen, dass der individuelle Kontakt zwischen Huf und Boden während der Stützbeinphase durch Trimmen und Beschlagen schwer zu beeinflussen ist (Hagen et al. 2016, Hagen et al. 2017, Hüppler et al. 2016).

2 Publikation I

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Review Article

Effect of Perineural Anesthesia on the Centre of Pressure (COP) Path During Stance Phase at Trot in Sound Horses

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ABSTRACT

This study aimed to examine how short-term loss of proprioception in the equine foot influences the individual COP path during the stance phase of the trot in sound horses. Ten horses were evaluated to be objectively non-lame using the 'Equinosis Q System and subsequently examined using a portable pressure measuring system with pressure foils fixed directly underneath both front hooves prior to and after perineural anesthesia of the palmar digital nerves. The individual COP paths of both forelimbs was assessed prior to and after unilateral and bilateral abaxial sesamoid nerve blocks. COP from initial contact to mid stance and breakover as well as the inter-stride variability were descriptively evaluated for each horse and limb. The individual COP path for each horse and limb during stance was shown to be highly repeatable without significant inter-stride variability. Location of initial contact, COP during midstance and breakover are not affected by unilateral or bilateral short-term loss of sensory feedback from the foot after perineural anesthesia. Anesthesia of the foot with an abaxial sesamoid nerve block does not affect the foot's COP during stance at a trot, therefore, sudden changes in gait pattern after perineural anesthesia should be interpreted with caution and warrant further clinical investigation.

Introduction

Evaluation of equine locomotion is the basis for diagnosing lameness and application of several orthopedic treatments such as trimming and shoeing of the hooves [1,2,32]. In several studies the pattern of the individual centre of pressure (COP) path from landing to last hoof-ground contact during the stance phase has been studied using force plates or pressure sensors [3–6]. As already stated by Nauwelaerts et al. (2017), any course of COP paths is possible in sound horses, and they are unique for each limb and individual [7]. Evaluation of the COP path during the stance phase provides insight into hoof-ground contact during locomotion under various conditions. Locomotion pattern depends on two interacting components – the CPG in the brain and spinal cord that produce signals to initiate leg movement, and peripheral proprioception which provides sensory input to the CPGs for modification of the initiated movements [7]. Peripheral inputs, like proprioception, are required to keep centrally generated patterns of limb movements smooth and coordinated [8]. It has been suggested that proprioceptive reflexes determine foot placement during initial contact at the beginning of the stance phase [9]. Commonly, proprioceptive signals from the hooves are assumed to be changed by trimming and shoeing with the aim to change equine gait and hoof-ground contact during locomotion in an intended way [3]. However, several authors have shown that it is difficult to alter the individual hoof-ground contact during the stance phase by trimming and shoeing [6,10,11]. It is questionable whether proprioception of the foot during stance is the major component determining the individual hoof-ground contact pattern during locomotion.

Animal welfare: This study was approved as an animal experiment by the Ethics Committee of the Thuringian state authority (Permit No: 15-006/16). Client-owned horses were included with informed consent.

Ethical statement: It can be confirmed that any handling and use of the horses in this study conforms to the code of practice for the care and use of animals for scientific purposes. The research adhered to the ethical requirements of the study country. This study was approved by the Ethics Committee of the Saxon state authority (Permit No: Permit No: 15-006/16). Client-owned horses were included with informed consent.

Conflict of interest statement: None of the authors have conflicts of interest.

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To the authors' knowledge, it is not known how short-term loss of proprioception in the equine foot influences the individual pattern of hoof-ground contact expressed by the COP path during stance in sound horses. A commonly used diagnostic tool considered as the gold standard to localize pain during clinical lameness examination is perineural anesthesia [12], by which nociception and proprioception in the distal limb is inhibited. Based on the described background, the following hypotheses have been formed:

The pattern of hoof-ground contact during stance, determined by the COP path, is individual for each horse and limb and is highly repeatable in sound horses.

The pattern of hoof-ground contact during stance is independent from proprioception of the hoof in sound horses.

Short-term loss of proprioception in the hoof due to application of nerve blocks at the level of the proximal sesamoid bones does not change the individual COP path of the forelimbs during stance.

Inter-stride variability of the individual COP path during stance does not increase after perineural anesthesia at the level of the proximal sesamoid bones.

Materials and Methods

Animals

From a population of 50 horses, 10 clinically sound and objectively non-lame horses, and without any history of lameness, were selected using subjective visual assessment by 2 independent observers and a commercially available inertial sensor-based system ('Equinosis Q with Lameness Locator software[a]). Both clinicians independently evaluated the horses according clinical guidelines for orthopedic examination using the AAEP score. All animals were observed in walk and trot on a straight line and in circles on firm and penetrable grounds. Horses with different assessments were re-evaluated. Established thresholds to objectively differentiate between lame and non-lame horses is a difference of vertical head movement < 6 mm and vertical symmetry of pelvic motion < 3 mm. Wither height of all horses was assessed with a horse measuring stick[b]. Weight was assessed using a standardized measuring tape for horses[c]. General health status was checked by two independent veterinarians. All horses included in this study had been regularly trimmed 5-7 weeks prior to the study and showed regular limb and hoof conformation. This study was approved as an animal experiment by the ethics committee of the state authority. Client-owned horses were included with informed consent.

Study design

All horses were examined with a pressure measurement system[d] to assess the individual COP path during stance phase in trot at the front hooves prior to any perineural anesthesia. Subsequently, the palmar nerves of the left forelimb of each horse were anaesthetized at the level of the proximal end of the proximal sesamoid bones. With the limb held off the ground by an assisting person, the neurovascular bundle was palpated over the abaxial margin of the sesamoid bones and 3 ml of 2% Mepivacain-hydrochloride solution[f] was injected subcutaneously along the medial and lateral palmar nerve, respectively, using 23G[e] needles. This perineural anesthesia desensitizes the entire foot [13]. The effect of the perineural anesthesia was tested after 10 min by exerting pressure on the skin at the level of the pastern with a pointed object [14]. Anesthesia was assessed as effective if the horse lost skin sensitivity proximal to the dorsal coronary band [15]. Thereafter, horses were re-evaluated again using the 'Equinosis Q system and a second pressure measurement was performed. Finally, palmar digital nerves of the right front limb were anaesthetized correspondingly, thereafter horses were re-evaluated with the 'Equinosis Q system and the hoof-ground contact was measured again.

Assessment of the COP Path During Stance

The shift of the COP during stance was assessed using a pressure measuring system[d] which recorded the vertical pressure affecting the solar surface of the hooves from initial to last hoof-ground contact. Thin sensor foils[g] (sampling rate: 240 fps, spatial resolution: 4 sensor cells/cm², thickness: 0.15 mm, 1-mm shim) were attached to the hooves with adhesive tape[h] [6,11]. The same sensor foil was used for all pre- and post-anesthesia examinations at one horse. The two sensors were connected to cuffs fastened to a polo wrap lateral to the distal metacarpus and a data logger attached caudal to the withers for wireless transmission of the data to a laptop computer with custom-made software. Horses were guided in their natural speed by an experienced handler along a straight line without lateral movement of the head in a consistent speed at a trot. Horses were examined on a plane concrete surface of 30 m over 10 seconds to obtain 10 – 12 regular strides for each horse and measurement. Speed was considered as comparable between measurements of each horse if an equal number of strides were recorded during the examination time of 10 seconds. The system was calibrated due to manufacturers' recommendations and previous publication [4].

Data analysis

Eight regular strides were averaged into one image showing the course of the center of pressure (i.e., the COP path) during stance phase for the left and right foot (Fig. 1). The first and the last stride of the measurement were excluded, respectively to avoid the influence of acceleration or deceleration at the beginning and ending of each measurement. The initial contact was defined as the moment the hoof had first contact with the ground, which was determined by the first-time pressure recording. Initial contact was represented by the start of COP path at the averaged pressure image (Fig. 1). The movement from initial contact toward mid stance represented the landing phase. Mid stance was defined as the moment when COP does not change significantly and maximal vertical pressure affects the hoof. The location of the COP during mid stance was automatically calculated by the software and displayed by a black-white box in the averaged pressure image (Fig. 1). Mid stance was followed by breakover starting with the lift-off of the heels until the last hoof- ground contact. Point of breakover, as the last hoof-ground contact, was shown as a black-white box at the end of the COP path (Fig. 1). The averaged pressure images, each for the left and right foot, were divided into 64 equal boxes for zoning of the pressure images into anatomical relevant regions. This zoning was applied to the averaged pressure images to analyze the location of initial contact, COP during mid stance and point of breakover. The description "flat landing" indicates that all parts of the weight bearing surface of the hoof have contact with the ground at the same time. Landing at the dorsal aspect of the weight bearing surface of the hoof is described as initial contact at the "medial or lateral toe". An initial contact at the lateral or medial weight bearing margin of the quarters is called "lateral or medial wall" landing. Horses showing an almost flat landing with a trend to the lateral or medial wall are described by landing with "lateral or medial tendency". An initial contact of both heels simultaneously is called landing with "central heels/frog" and unilateral heel landing with landing at the "lateral or medial heel". Inter-stride variability of initial contact was evaluated by assessing the location of initial contact in each single stride at the left and right foot belonging to one walk (n = 8) of one horse pre-anesthesia and calculating the number of strides deviating from

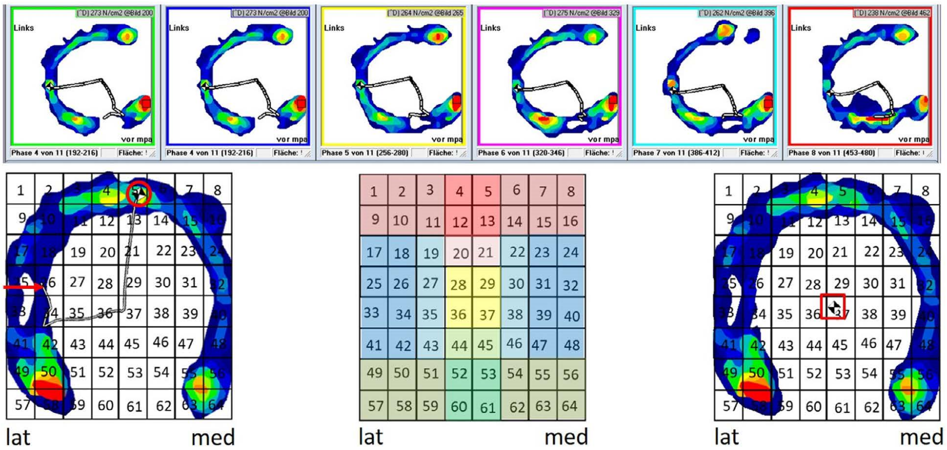

Fig. 1. Averaged pressure images of eight recorded consecutive stance phases (the Tekscan software does not enable a screenshot of more than six strides) showing the COP path of the left hoof of horse (no. 1 in Table 1). The left image shows location of initial contact (red arrow) and the location of the point of breakover (red circle). The right image shows the location of the COP during mid stance (red box). The middle image shows the applied zoning of the images into: lateral toe (box 1,2,3,9,10,11), central toe (box 4,5, 12,13, 20, 21), medial toe (box 6,7,8,14,15,16), lateral wall (box 17,18,25,26,33,34,41,42), lateral tendency (box 19,27,35,43), medial wall (box 23,24,31,32,39,40,47,48), medial tendency (box 22,30,38,46), flat/central (box 28,29,36,37, lateral heel (box 49,50,51,57,58,59), central heels/frog (box 44,45,52,53,60,61), medial heel (box 54,55,56,62,63,64)

Table 1
Location of initial contact in each stride used to calculate the averaged initial contact of n = 8 strides (Average Ø) of all horses before and with bilateral anesthesia.

Horse	Status	Step2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Average (Ø)	N ≠ Ø
1	**Pre anest.**	26	26	26	25	26	26	25	26	**26**	**2**
	bilat. anaest.	18	25	26	26	26	26	25	26	**26**	**3**
2	**Pre anest.**	29	30	29	29	29	29	30	29	**29**	**2**
	bilat. anest.	29	29	28	28	29	29	29	29	**29**	**2**
3	**Pre anest.**	36	36	36	35	36	29	36	35	**36**	**3**
	bilat. anaest.	38	37	36	36	36	36	36	37	**36**	**3**
4	**Pre anest.**	34	27	26	35	35	35	35	35	**35**	**3**
	bilat. anaest.	34	35	34	35	35	35	34	35	**35**	**3**
5	**Pre anest.**	27	35	27	35	35	34	35	27	**35**	**4**
	bilat. anaest.	27	27	27	28	27	27	28	27	**27**	**2**
6	**Pre anest.**	28	28	29	22	28	28	23	28	**28**	**3**
	bilat. anest.	28	38	28	28	29	28	28	29	**28**	**3**
7	**Pre anest.**	37	46	46	37	46	46	38	46	**46**	**3**
	bilat. anaest.	38	38	38	37	38	38	37	38	**38**	**2**
8	**Pre anest.**	29	30	28	28	28	29	28	29	**28**	**4**
	bilat. anaest.	36	28	29	28	21	28	28	28	**28**	**3**
9	**Pre anest.**	20	29	28	29	28	28	28	20	**28**	**4**
	bilat. anaest.	28	29	28	28	29	28	29	28	**28**	**3**
10	**Pre anest.**	34	26	27	26	27	27	27	26	**27**	**4**
	bilat. anaest.	27	26	27	27	27	26	26	27	**27**	**3**

In the last column, the number of strides deviating from the averaged initial contact (N ≠ Ø) are shown as an indicator for inter stride variability. The first and last stride have been excluded from analysis

the averaged initial contact of this walk (Table 1). The location of each motion event was compared between the status before any anesthesia, with unilateral anesthesia (left foot only), and bilateral anesthesia (left and right foot). Results were described in descriptive analysis and cross tables.

Results

From the population of 50 horses, 10 horses (Table 2) fulfilling the required criteria of being non-lame as assessed with the 'Equinosis Q System and two independent veterinarians and without any history of lameness were used for the examinations.

COP paths during trot showed different courses in all examined horses and limbs. Repeatability of COP paths, represented by location of initial contact, COP during mid stance and point of breakover, at a trot was high in all horses. Inter-stride variability was low (Table 1).

Prior to perineural anaesthesia, the majority of the horses showed either a flat landing pattern (left hooves: n = 5, right hooves: n = 3) or a tendency for lateral landing (left hooves: n = 4, right hooves: n = 4) (Table 3). Furthermore, landing at the lateral wall occurred (left hooves: n = 1, right hooves: n = 2). One horse showed initial contact at the toe of its right hoof. During mid stance, COP shifted centrally in all horses (Table 3). Most of the animals showed breakover at the lateral aspect of the distal hoof wall (left hooves: n = 6, right hooves: n = 4). In some horses, breakover occurred at the central aspect of the dorsal part of the distal margin (left hooves: n = 4, right hooves: n = 5) and in one horse

Table 2
Signalment of non-lame equids included in the current study (individuals marked with * were examined to assess COP path in previous studies from 2013 - 2017).

Horse	Breed	Age (years)	Wither Height (cm)	Weight (kg)
1	German Riding Pony*	15	140	458
2	German Riding Pony*	11	146	436
3	German Riding Pony	14	145	430
4	German Riding Pony	7	120	345
5	Polish Warmblood	6	152	432
6	Oldenburger Warmblood	6	160	504
7	German Warmblood*	5	167	582
8	German Warmblood*	8	172	620
9	German Warmblood	9	172	650
10	Zweibrücker Warmblood	25	167	520
Mean		**10.60**	**154.10**	**497.70**
SD		**5.78**	**15.88**	**91.32**

Table 3
Location of initial contact with the corresponding box (IC) and its equivalent anatomical region (IC region), COP during mid stance (Mid) and point of breakover with the corresponding box (BO) and its anatomical region (BO region) before anesthesia (pre anest), with unilateral left anesthesia (unilat. anest) and bilateral anesthesia (unilat. anest)

		left					**right**				
Horse	**Status**	**IC**	**IC Region**	**Mid**	**BO**	**BO Region**	**IC**	**IC Region**	**Mid**	**BO**	**BO Region**
1	Pre anest.	26	lateral wall	37	5	central toe	25	lateral wall	36	4	central toe
	unilat. anaest.	26	lateral wall	37	5	central toe	26	lateral wall	36	4	central toe
	bilat anest.	26	lateral wall	37	5	central toe	26	lateral wall	36	12	central toe
2	Pre anest.	29	flat	37	3	lateral toe	29	flat	37	3	lateral toe
	unilat. anest.	37	flat	36	3	lateral toe	29	flat	37	3	lateral toe
	bilat. anaest.	29	flat	37	3	lateral toe	29	flat	37	3	lateral toe
3	Pre anest.	36	flat	37	3	lateral toe	34	lateral wall	36	3	lateral toe
	unilat. anest.	36	flat	37	3	lateral toe	26	lateral wall	36	4	central toe
	bilat anest.	36	flat	37	3	lateral toe	34	lateral wall	36	3	lateral toe
4	Pre anest.	35	lat tendency	36	3	lateral toe	35	lat tendency	36	4	central toe
	unilat. anest.	35	lat tendency	36	3	lateral toe	35	lat tendency	36	4	central toe
	bilat. anest	35	lat tendency	36	3	lateral toe	35	lat tendency	36	3	lateral toe
5	Pre anest.	35	lat tendency	36	3	lateral toe	27	lat tendency	36	3	lateral toe
	unilat. anest.	27	lat tendency	36	3	lateral toe	28	flat	36	3	lateral toe
	bilat anest.	27	lat tendency	36	3	lateral toe	28	flat	36	11	lateral toe
6	Pre anest.	28	flat	37	3	lateral toe	27	lat tendency	37	4	central toe
	unilat. anest.	28	flat	37	3	lateral toe	27	lat tendency	37	4	central toe
	bilat. anaest.	28	flat	37	3	lateral toe	27	lat tendency	37	4	central toe
7	Pre anest.	46	lat tendency	37	11	lateral toe	36	flat	37	10	lateral toe
	unilat. anest.	46	lat tendency	37	12	lateral toe	36	flat	37	11	lateral toe
	bilat anest.	38	lat tendency	37	11	lateral toe	35	lat tendency	36	10	lateral toe
8	Pre anaest.	28	flat	37	5	central toe	28	flat	36	5	central toe
	unilat. anest.	29	flat	37	4	central toe	36	flat	36	5	central toe
	bilat. anaest.	28	flat	37	4	central toe	28	flat	36	5	central toe
9	Pre anest.	28	flat	29	13	central toe	21	toe	28	5	central toe
	unilat. anest.	29	flat	29	13	central toe	20	toe	28	5	central toe
	bilat anest.	28	flat	29	13	central toe	21	toe	28	5	central toe
10	Pre anest.	27	lat tendency	29	5	central toe	27	lat tendency	28	6	medial toe
	unilat. anest.	27	lat tendency	29	5	central toe	27	lat tendency	28	6	medial toe
	bilat. anest	27	lat tendency	29	14	lateral toe	27	lat tendency	28	6	medial toe

breakover was present at the medial aspect of the dorsal part of the distal margin at the right hoof (Table 3).

Six out of ten horses showed bilateral left-right symmetry in their pattern of the COP path. In the other horses, obvious left-right differences of the COP path occurred (Fig. 2).

After anesthesia of the palmar digital nerves at the left foot, the individual pattern of the COP path of the blocked hooves was the same as pre-block in 6 horses (Fig. 3). In four horses, minor changes of the initial contact appeared, but the location of first hoof-ground contact did not change more than one box and remained in the same hoof region (Table 3,4). The location of the COP during mid stance was not influenced by unilateral perineural anesthesia in any horse. The point of breakover stood unaffected by the anesthesia in 8 horses. Two horses showed a shift in the point of breakover about one box, but again within the same region at the toe. Similar results were demonstrated for the still non-anesthetized right feet – the pattern of the COP path, represented by the location of initial contact, COP during mid stance and breakover, remained the same compared to the status prior to contralateral anesthesia in nine out of ten horses (Table 2). after abaxial sesamoid nerve blocks were performed in both front feet, none to minimal changes to the pattern of the COP path occurred in any of the horses. (Fig. 3). Only at two horses a change of initial contact became visible compared to the situation before anesthesia. However, the change of initial contact was still within the same hoof region and shift was not more than one box (Table 3,4). Location of the COP during mid stance was not influenced by bilateral perineural anesthesia. In addition, two horses (no. 1 + 5) showed a shortened breakover, but in the other eight horses, location of the point of breakover stood unaffected by bilateral nerve blocks.

Inter-stride variability of the COP path did not increase following anesthesia of the palmar digital nerves of both feet in any horse (Table 2, Fig. 4). Table 2 shows the location of initial contact of each step of the left limb presented separately for all horses before any treatment and after bilateral anesthesia. In addition, the

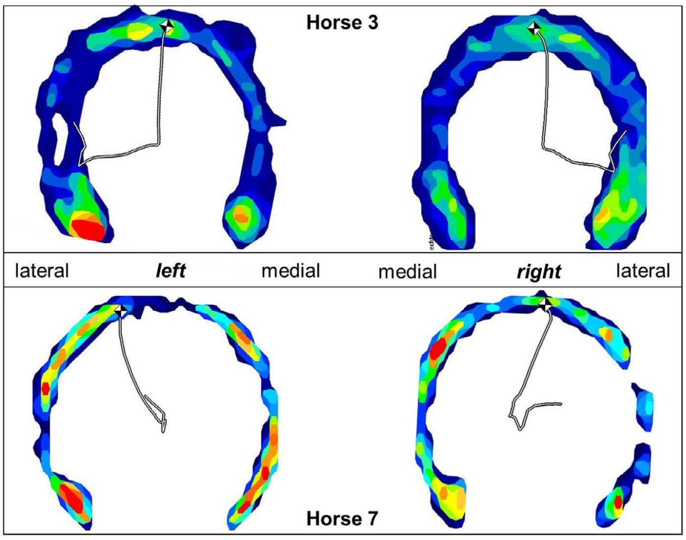

Fig. 2. Comparison of the COP path of the left and right hoof in: (A) one horse (no. 1) showing bilateral symmetry of the COP path and (B) another horse (no. 2) showing a left-right difference of the COP path at both forelimbs in trot.

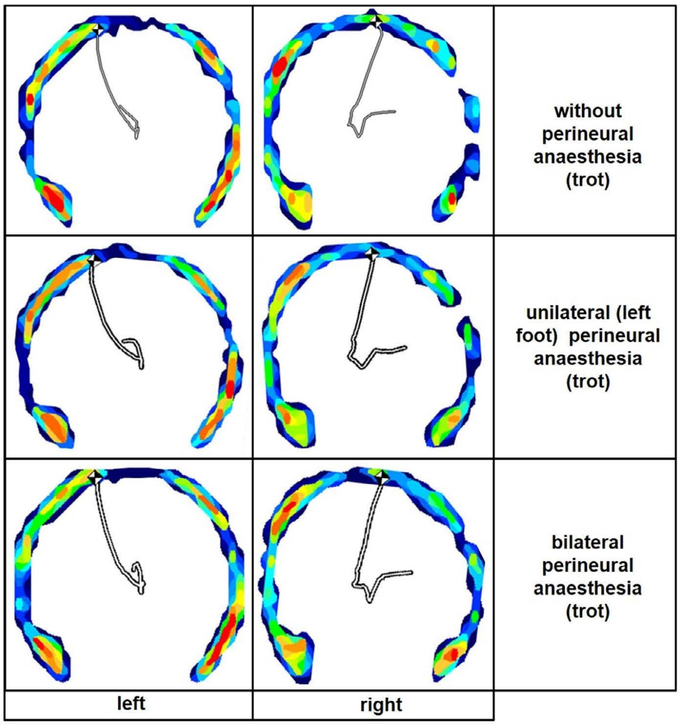

Fig 3. Effect of unilateral and bilateral perineural anesthesia on the COP path at both front hooves of one horse as an example for the results of the current study (horse no. 2).

Table 4
Percentage distribution of initial contact in the four relevant anatomical regions (toe, lateral wall = lat. wall, lateral tendency = lat. tend., and flat) at the left and right limb before (pre anest.), with unilateral (unilat. anest) and with bilateral anesthesia (bilat. anest)

		Location of Initial Contact							
Limb	**Status**	Lat. Toe	%	Lat. Wall	%	Lat. Tend.	%	Flat	%
left	**Pre anest.**	0	0%	1	10%	4	40%	5	50%
	unilat. anest.	0	0%	1	10%	4	40%	5	50%
	bilat. anest.	0	0%	1	10%	4	40%	5	50%
right	**Pre anest.**	1	10%	2	20%	4	40%	3	30%
	unilat. anest.	1	10%	2	20%	3	30%	4	40%
	bilat. anest.	1	10%	2	20%	4	40%	3	30%

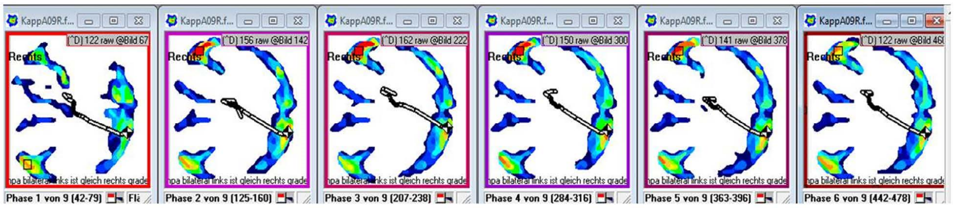

Fig 4. Pressure images of six recorded consecutive stance-phases showing the COP path of the right hoof of one horse (no. 2) after bilateral perineural anesthesia at trot (the Tekscan software does not allow to screenshot more than six strides).

number of strides deviating from the averaged location of initial contact is shown to support the stated findings.

Changes of pressure distribution dependent on perineural anesthesia occurred, but will be separately published elsewhere.

Discussion

The current study showed that the individual COP path is highly repeatable for each horse and limb and it remains unaffected by a short-term loss of proprioception in the feet caused by perineural anesthesia. To the authors' knowledge, effects of perineural anesthesia at the distal limb on COP path, limb placement, or hoof-ground contact during motion in sound horses have not been examined before. Previous studies investigated the effect of low palmar nerve blocks on gait symmetry and kinetic parameters using semiquantitative visual assessment [17,18]. Keg et al. (1996) showed no changes of clinical scores in equine gait pattern after nerve blocks in sound horses. Moreover, no significant effects of perineural anesthesia on peak vertical force, vertical impulse and stance time in sound horses were demonstrated [18]. Based on these results, this group concluded that diagnostic nerve blocks do not significantly alter the gait of a sound horse, what can be supported by the findings of the current study. This statement was also confirmed by van de Water et al. (2015), who showed that low palmar digital and abaxial sesamoid nerve blocks do nor have an effect on limb loading or toe–heel and mediolateral hoof balance in sound horses [19]. Contrarily, Kübber et al. (1994) showed an influence of low palmar nerve blocks on the equine gait. However, changes were related to acceleration of head and wither. Horses nodded their heads and lowered their withers significantly more while loading the blocked limb [17]. Only Moorman et al. (2014) found an increase in standard deviation of sagittal orientation of the hooves following perineural anesthesia in clinically normal horses [20].

Conclusively, corresponding to results of the current study the first hypothesis can be confirmed: In sound horses different shapes of COP path patterns were detected in the current study, which corresponds to the findings of various groups using force plates or pressure sensors for motion analysis [3,6,21]. The stated groups detected all types of landing pattern. In the current study, flat and lateral landing occurred most frequently. In most previous studies lateral landing was visible in the majority of horses with up to 74% in walk [3,4,22]. Flat landing was only present with 12% to 21%, which is a lower percentage than in the current study (50 %). In a long-term study of 70 horses investigating the effect of different trimming methods on the pattern of the COP path during walk, 38% showed a lateral and 40% a flat landing, which is comparable to the data of the current study [6]. The difference between results with regard to the location of initial contact might be related to the selection criteria of horses. The current study excluded animals with severe limb deviations, since Martens et al. (2008) showed that the greater the mediolateral deviation in the fetlock, the less likely a flat landing occurred [23]. In general, results with regard to the gait pattern and COP path might be dependent on the selected population and the sample size.

As shown in the present study and by Nauwelaerts et al. (2017), repeatability of the pattern of the COP path during consecutive stance phases in trot on a straight, plane surface is very high [21]. Additionally, as shown in the current findings and prior investigations, COP path is horse and limb dependent [21].

In the current study only 60% of horses showed a similar COP path between left and right limb. In the other horses there was no symmetry in the COP migration during the stance phase in trot. In particular, location of initial contact showed bilateral differences. This is in contrast to the findings of a previous study in which it was stated that COP path in the mediolateral direction has a high correlation between left and right limb [21]. The assessed left-right differences in COP path might be related to anatomical asymmetries in the locomotor system, leading to functional asymmetry in the equine gait pattern [21,24]. Individual COP paths might reflect long-term adaption dependent on the conformation and functionality of the proximal locomotor system [25–27], such as shoulder, trunk, chest, pelvis, and back.

Furthermore, the current study showed that loss of proprioception at the level of the hoof due to unilateral or bilateral anesthesia of the palmar digital nerves at the level of the fetlock does not change the individual COP path of the forelimbs during stance. These findings corroborate to the first part of the second hypothesis: The pattern of hoof-ground contact during stance in trot on a straight, plain surface seems to be independent from proprioception of the hoof. Furthermore, no stumbling or any hesitancy during trot was observable after perineural anesthesia. This was reflected by the fact that inter-stride variability of the individual COP path during stance was not increased by nerve blocks at the level of the proximal sesamoid bones, confirming the second part of the second hypothesis. This might be related to the fact that long-term defined and established spinal circuits for locomotor control determine precise timings and patterns of repetitive locomotor movements in vertebrates [29]. Due to neuroplastic changes in the central nervous system, basic motor learning strategies enable adaption of gait function and locomotor pattern dependent on different inputs, such as proprioception of the hoof but also and probably more important to muscle development, training, ageing, or pain [30]. Muscle spindle cells in the muscles of the proximal locomotor system give the fastest proprioceptive input compared to mechanoreceptors located in structures of the distal limb, such as Golgi tendon organ or Renault bodies [31].

Flexor–extensor pattern-generating circuits are needed for intra-limb coordination determined by way and intensity of muscle contraction to move the limb during gait [28,29]. These central pattern generators in the spinal cord and the brain ensure efficient locomotion in complex environments, which is key to animals' survival and might also determine individual COP paths of horses walking on firm and plain ground. They might be even more important for limb placement and hoof-ground contact during repetitive motion than proprioceptive information from the hooves. This fact would also explain the findings of previous examinations, which showed that different trimming methods or application of modified horseshoes have a very limited short-term or long-term influence on the COP path in walk and trot [6,10,11,16,22], although it is assumed that the trimming and shoeing cause a change in proprioception in the hooves [3]. Rather, movement of the limb during the swing phase and conformation of the proximal locomotor system determine limb placement during landing [22,23], which in turn is related to conformation of the proximal locomotor system and neuromuscular circuits [7,8]. The COP path of each horse and each limb can be defined as a result of dynamics occurring in the proximal locomotor system. The motor control of each limb and its dynamics have been shaped in such a way that the limb moves optimally [28,29]. Anatomical asymmetries, lateralized training, or pain seem to interfere with these biomechanically and neurologically predefined locomotor patterns rather than changes in proprioception in the hooves caused for example by trimming and shoeing [28].

In conclusion, the present study demonstrates that the individual COP path for each horse and limb during stance is highly repeatable and is not affected by short-term loss of the sensory feedback from the foot using perineural anesthesia. Proprioception of the hoof is undoubtedly an important part of the sensory feedback mechanism in horses walking over uneven or rocky terrain to avoid overload or injuries [8]. However, a rhythmic and repeated gait pattern on a plane surface without the need for fine tuning and adaption to surface conditions as required by the horses in the current study seems to be less dependent on sensory information from the hoof.

Central pattern generators (CPG) probably dominate determination of the locomotion pattern in swing and stance and might interfere with the effect of trimming and shoeing or any change of hoof proprioception. Since the COP path during stance is the result of numerous factors such as body conformation, kinematics of trunk and limbs, hoof-ground interaction, and neuromuscular pathways, it is hard to theoretically predict the optimal COP path for a given individual [6,21]. Since perineural palmar nerve anesthesia does not affect the individual pattern of hoof-ground contact during stance, sudden changes in the individual gait pattern after local perineural anesthesia should be interpreted carefully and warrant further clinical investigation.

Submission Declaration and Verification

The manuscript has not been published previously and it is not under consideration for publication elsewhere. Its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out. If accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder

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3 Publikation II

animals

MDPI

Article

Bilateral Change in Vertical Hoof Force Distribution in Horses with Unilateral Forelimb Lameness before and after Successful Diagnostic Anaesthesia

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Simple Summary: Lameness is the most common cause of reduced performance in equids. Therefore, its detection, accurate diagnosis, and appropriate treatment are important for animal welfare and economics. Subjective evaluation of a lame horse by visual assessment is prone to error. To objectify the examination, several computer-based systems have been developed. While kinematic investigations focus on the detection of movement asymmetries (e.g., of head, pelvis, withers) with the help of position sensors, kinetic examinations are based on pressure measurement under the hooves. In the current study, horses with unilateral forelimb lameness were equipped with a non-invasive pressure measurement system on both forelimbs simultaneously. Bilateral vertical force distribution (in kg) was evaluated during all phases of stance (landing, midstance, breakover) before and after diagnostic anaesthesia. Vertical force was reduced on the lame limb compared to the sound limb before diagnostic anaesthesia. After positive diagnostic anaesthesia, asymmetries were neutralised: vertical force increased on the lame limb, with breakover being most affected. In conclusion, the current pressure measurement system can be used to objectify lameness examinations in a clinical setting. Both lameness and diagnostic anaesthesia influence the particular phases of stance differently. This might contribute to a better understanding of equine gait and lead to individually optimised shoes.

Abstract: Kinetic examinations of horses with induced lameness as well as the effect of perineural anaesthesia in sound horses have shown promise, but clinical studies regarding the effect of diagnostic anaesthesia during the different stance phases are rare. Fourteen horses with unilateral forelimb lameness were examined with the Hoof™ System during trot to assess vertical force distribution (in kg) affecting both front hooves before and after diagnostic anaesthesia during landing, midstance, and breakover. For statistical analysis, a covariance analysis with repeated measurements regarding the limb (lame/sound) as well as anaesthesia (before/after) and the covariable body weight was performed. The p-values for the pairwise comparisons were adjusted using the Bonferroni–Holm correction ($p < 0.05$). For all phases of the stance, a significant interaction between the factors limb and anaesthesia was shown. Before diagnostic anaesthesia, vertical force was significantly reduced on the lame limb compared to the sound limb during landing (−25%, $p < 0.001$), midstance (−20%, $p < 0.001$) and breakover (−27%, $p < 0.001$). After anaesthesia, the difference between both forelimbs was not significant anymore for all phases. The vertical force on the lame limb increased significantly after positive anaesthesia during the whole stance phase, with breakover being most affected (+27%, $p = 0.001$). Pressure measurements with the Hoof™ System can be used to evaluate the effect of diagnostic anaesthesia in a clinical setting with pain-related vertical force asymmetries being neutralised after diagnostic anaesthesia. Breakover is the main event influenced by lameness.

Keywords: equine gait; stance phase; breakover; diagnostic anaesthesia; kinetics; Hoof™ System

1. Introduction

Visual evaluation of a lame horse before and after diagnostic anaesthesia is part of a standard lameness investigation. However, the objectivity of this method is limited, and it can often be an inaccurate assessment method [1–5].

To objectively quantify gait abnormalities, several inertial sensor-based and kinetic systems, such as pressure mapping-based systems, have been developed [6–11]. However, until now, kinetic evaluations have focussed on the effect of perineural anaesthesia in sound horses and those with experimentally induced lameness [12–16], while clinical studies are rare [17].

Pressure measurements may either be performed with systems embedded in the runway [10] or with foil-based systems fixed to the hooves. The latter provides the analysis of bilateral pressure distribution during clinical lameness examinations, as they enable the analysis of multiple, consecutive strides under various conditions without noticeable interference with the physiologic gait pattern of the horse [18,19]. Pressure distribution of the loading area during the different phases of the stance phase can be evaluated [20]. Previous studies showed that pressure distribution under the hoof in lame horses varies depending on the underlying pathology [21].

The objective of the present study was to determine the effect of diagnostic anaesthesia on bilateral vertical force distribution (in kg) in horses with unilateral forelimb lameness during all phases of the stance phase by using a non-invasive pressure measurement system (Tekscan Hoof System®, Tekscan®, Inc., South Boston, MA, United States) on both forelimbs simultaneously.

The following hypotheses were tested:

1. Before diagnostic anaesthesia
    (a) Vertical force in kilograms on the lame limb is reduced compared to the sound limb during all parts of the stance phase (landing, midstance, breakover).
2. After positive diagnostic anaesthesia
    (a) Vertical force on the anaesthetised limb increases whereas the vertical force on the sound limb decreases, which leads to a more symmetrical bilateral vertical force distribution in kilograms during all parts of the stance phase (landing, midstance, breakover).
    (b) Following diagnostic anaesthesia, the maximum increase in vertical force on the lame limb occurs during midstance.

2. Materials and Methods

2.1. Horses

Data were acquired prospectively from 14 horses with unilateral forelimb lameness that were referred for lameness examination. After anamnesis and a general examination, a complete orthopaedic examination was performed by two independent experienced veterinarians, and the indication for diagnostic anaesthesia was confirmed. Lameness severity was divided into five degrees using a modified AAEP lameness score [3], using half units (e.g., 3.5) at the discretion of the examining clinician. Weight of the horses was estimated by measuring the chest circumference (Horse & Pony Weighing Tape, William Hunter Equestrian, Littlehampton, UK).

2.2. Data Collection

All horses were examined with the Hoof™ System (TekScan®, TekScan Hoof System®) to assess vertical force (in kg) affecting both front hooves before and after diagnostic anaesthesia (Figure 1). The 0.15 mm thin sensor foils (Hoof Sensors Model #3200E, Tekscan, Inc., South Boston, United States) of the system detect vertical pressure with a spatial resolution of 3.9 sensor cells/cm^2 and a recording frequency of 250 Hz (Figure 2). After cutting the sensor foils to the respective size of the hooves they were protected on both sides with a self-adhesive 2 mm thick foam rubber layer (3M Deutschland GmbH, Neuss, Germany) (Figure 3) and fixed underneath both front hooves with adhesive tape (Tesa Duct Tape 4610, Global Headquarters—Tesa SE, Norderstedt, Germany). The connector of the sensor was inserted into the data logger on the lateral side of each forelimb. Before each measurement calibration was performed according to the manufacturers' instructions and previous publications [18,22]. Subsequently, horses were trotted on hand at their natural speeds for 10 seconds in a straight line on a hard surface without sideway movements or excessive interaction with the leading person on the left-hand side of the horse while data were recorded and stored.

Figure 1. Horse equipped with the Hoof™ System.

Afterwards, diagnostic anaesthesia of the affected leg was performed from distal to proximal by using defined volumes of 2% mepivacaine hydrochloride solution (Mecain® 20 mg/mL: Puren Pharma GmbH & Co. KG, München, Germany) according to clinical guidelines [23,24]. Five to ten minutes post-injection, the effect of each regional nerve block was assessed by testing the skin sensitivity using a blunt item. Effectiveness of diagnostic intraarticular anaesthesia was assessed by obtaining a reflux of synovial fluid after needle placement into the synovial cavity and by clinical response.

Ten minutes after diagnostic anaesthesia, the horses were trotted again as described above to evaluate the subjective lameness degree. After successful anaesthesia, a second measurement with the Hoof™ System was performed.

Examination protocols were standardised regarding the position of handler and timings following diagnostic anaesthesia. Horses were allowed to trot at their natural speed in a controlled environment ensuring regular movement during our investigations. Only strides from a regular segment were analysed, discarding the first and last strides to eliminate the effects of acceleration and deceleration.

Figure 2. Sensor foil of the Hoof™ System.

Figure 3. Prepared sensor foil.

2.3. Data Analysis

After completed measurement, data were transferred to the software program FastSCAN Mobile Research Version 6.68® (FastSCAN Mobile Research Version 6.68® (Tekscan®), Inc., South Boston, MA, USA), displaying the information as averaged two-dimensional colour-coded pressure images (Figure 4) and as averaged pressure–time curves (Figures 5 and 6). Generally, eight to ten consecutive strides were used for further calculations of the parameters of interest.

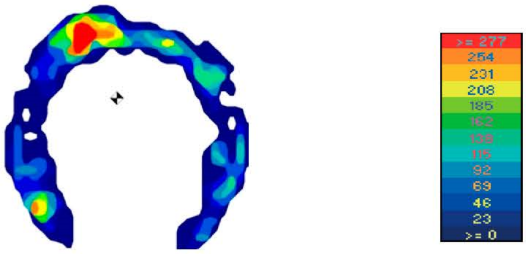

Figure 4. Averaged two-dimensional colour-coded pressure image during midstance. With a colour scale, the different pressure distributions (N/cm^2) can be distinguished within the weight-bearing surface of the hoof (see pressure scale on the right side). In this study, data were converted to kilograms.

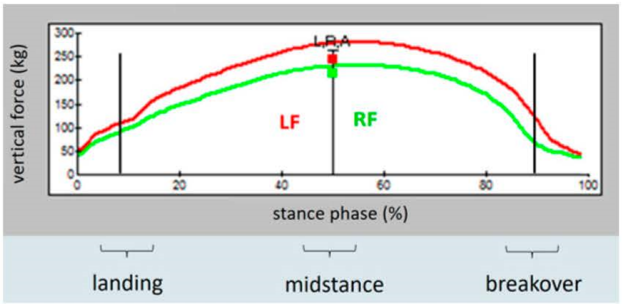

Figure 5. Averaged pressure–time curve of one horse in the current study with right forelimb lameness: vertical force in kg on the left (red) and the lame right (green) forelimb during landing (10% of the stance phase), midstance (50% of the stance phase), and breakover (90% of the stance phase) before anaesthesia.

The averaged pressure–time curves allowed for analysis of the vertical force distribution (in kg) at each single hoof and the difference between both forelimbs during landing, midstance, and breakover (Figures 5 and 6). The x-axis of this curve shows the time of the whole stance phase. Approximately the first 20% of stance phase represents landing, followed by midstance, lasting until 80% of the time of stance phase. The last 20% represents breakover [25,26]. Representative points in time were used to assess vertical force exerted on the ground during landing (at the 10% point of stance phase in the pressure-time curves), midstance (at the 50% point of stance phase), and breakover (at the 90% point of stance phase) (Figures 5 and 6).

For statistical analyses of the data, the software BMDP/Dynamic (BMDP Statistical Software Manual 1992: BMDP Release 8.1. University of California Press, Berkeley, CA, USA) was used. All variables were tested prior to the statistical analysis for normal distribution using the Shapiro–Wilk test. For each variable (vertical force in kilograms on both front hooves before and after diagnostic anaesthesia during landing, midstance, and breakover), a two-way analysis of covariance (ANCOVA) with repeated measurements regarding the factors limb (lame/sound) and anaesthesia (before/after) and the covariable body weight was performed. $p < 0.05$ was regarded as statistically significant. The p-values for the pairwise comparisons were adjusted using the Bonferroni–Holm correction.

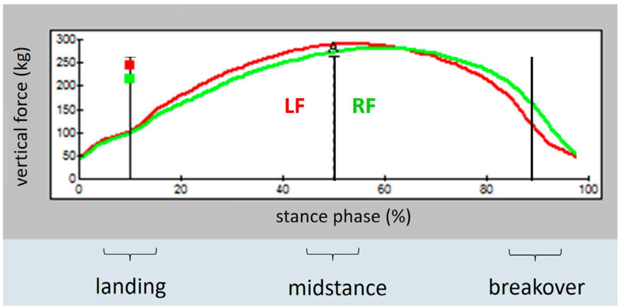

Figure 6. Averaged pressure-time-curve of one horse in the current study with right forelimb lameness: vertical force in kg on the left (red) and anaesthetised right (green) forelimb during landing (10% of the stance phase), midstance (50% of the stance phase), and breakover (90% of the stance phase) after anaesthesia.

3. Results

Fourteen horses with unilateral forelimb lameness fulfilled the inclusion criteria. Horse descriptions are given in Table 1. Results of the lameness examination and diagnostic anaesthesia are shown in Table 2. On average, the 14 orthopaedic patients showed a mean lameness score of 2.4 ± 0.7/5 in a straight line on hard ground. Altogether, 10 perineural anaesthesia at the distal limb, 3 intrasynovial anaesthesia and 1 regional infiltration of the medial collateral ligament of the elbow joint with local anaesthetic were performed. Four cases were sound after regional or intrasynovial anaesthesia, seven cases showed a substantial reduction in lameness, lameness improved in one case and horses developed contralateral limb lameness following diagnostic anaesthesia in two cases (Table 2).

Table 1. Signalment of horses (age, weight, shod/unshod) with forelimb lameness included in the current study, divided by breed.

Breed	Age (Mean ± SD)	Weight (Mean ± SD)	Shod	Unshod
8 German Warmblood horses	12 ± 6 years	560 ± 50 kg	4 *	4
2 Icelandic horses	10 ± 5 years	350 ± 50 kg	0	2
2 Cold bloods	15 ± 2 years	650 ± 50 kg	2 †	0
1 Appaloosa	16 years	500 kg	1 †	0
1 Arabian horse	22 years	400 kg	0	1

* 2 × standard shoes, 1 × spider plate shoe, 1 × Eggbar shoe, † normal shoes.

Table 2. Results of lameness examination of horses with forelimb lameness included in the current study involving the breed, the lame forelimb, and the lameness score as well as location, type, and result of anaesthesia.

	Lame Limb	Lameness Score	Location of Anaesthesia	Type of Anaesthesia	Result of Anaesthesia
Warmbloods					
1	RF	2	antebrachiocarpal joint	intrasynovial	positive
2	LF	2	digital flexor tendon sheath	intrasynovial	positive with slight rest
3	RF	3.5	abaxial sesamoid	perineural	positive with lameness on the contralateral limb
4	RF	3	abaxial sesamoid	perineural	positive with slight rest
5	RF	2	abaxial sesamoid	perineural	positive with slight rest
6	LF	2	abaxial sesamoid	perineural	positive
7	RF	2	abaxial sesamoid	perineural	positive

Table 2. *Cont.*

	Lame Limb	**Lameness Score**	**Location of Anaesthesia**	**Type of Anaesthesia**	**Result of Anaesthesia**
8	RF	3	medial collateral ligament (elbow joint)	infiltration	positive with distinct rest
Icelandic horses					
9	LF	1	high 4 point	perineural	positive with slight rest
10	LF	2	low palmar digital	perineural	positive
Cold bloods					
11	RF	2	high palmar digital	perineural	positive with lameness on the contralateral limb
12	RF	3	low 4 point	perineural	positive with slight rest
Appaloosa					
13	RF	2	abaxial sesamoid	perineural	positive with slight rest
Arabian horse					
14	RF	3.5	antebrachiocarpal joint	intrasynovial	positive with slight rest

3.1. *ANCOVA*

The statistical analysis showed a significant interaction between the factors limb and anaesthesia for all phases of stance. The body weight showed a significant impact on the dependent variables (see Table 3). Due to the results of the ANCOVA, pairwise comparisons were made.

Table 3. Results of the ANCOVA. Global p-values for the repeated measurements limb (lame/sound) and anaesthesia (before/after), as well as their interaction and the covariable body weight during landing, midstance, and breakover.

	Landing	**Midstance**	**Breakover**
Impact of body weight	$p = 0.001$	$p < 0.001$	$p = 0.02$
Impact of limb (lame/sound)	$p = 0.008$	$p = 0.003$	$p = 0.02$
Impact of anaesthesia (before/after)	$p = 0.6$	$p = 0.2$	$p = 0.5$
Interaction between limb and anaesthesia	$p = 0.003$	$p < 0.001$	$p < 0.001$

3.2. *Pairwise Comparisons*

3.2.1. Before Diagnostic Anaesthesia

Before diagnostic anaesthesia, vertical force was significantly reduced on the lame limb compared to the sound limb during landing (−25%, $p < 0.001$), midstance (−20%, $p < 0.001$), and breakover (−27%, $p < 0.001$) (Table 4).

Table 4. Pairwise comparisons of the bilateral vertical force in kg between the sound and the lame limb before anaesthesia during landing, midstance, and breakover.

	Lame Limb	**Sound Limb**	***p*-Value**
Landing	111 ± 28 kg	147 ± 45 kg	<0.001
Midstance	265 ± 75 kg	332 ± 110 kg	<0.001
Breakover	135 ± 71 kg	185 ± 87 kg	<0.001

3.2.2. After Diagnostic Anaesthesia

After diagnostic anaesthesia, the bilateral vertical force distribution became more symmetrical. Still, the horses continued to exert less vertical force in kg on the anaesthetised limb during landing (−6%, $p = 0.1$) and midstance (−3%, $p = 0.3$), whereas during breakover, the horses exerted more vertical force on the anaesthetised limb when compared to the sound limb (+5 %, $p = 0.3$). This bilateral difference in vertical force distribution was not significant in any motion event (Table 5).

Table 5. Pairwise comparisons of the bilateral vertical force in kg between the sound and the lame limb after anaesthesia during landing, midstance, and breakover.

	Lame Limb	Sound Limb	*p*-Value
Landing	127 ± 34 kg	136 ± 35 kg	0.1
Midstance	307 ± 76 kg	318 ± 79 kg	0.3
Breakover	170 ± 73 kg	162 ± 63 kg	0.3

3.2.3. Lame Limb before and after Anaesthesia

The vertical force on the lame limb increased significantly after positive anaesthesia during all motion events (landing +15%, $p = 0.009$; midstance +16%, $p < 0.001$). The main increase in vertical force after anaesthesia was observed during breakover (+27%, $p = 0.001$) (Table 6).

Table 6. Pairwise comparisons of the vertical force in kg on the lame limb before and after anaesthesia during landing, midstance, and breakover.

	Lame Limb: Vertical Force before Anaesthesia	Lame Limb: Vertical Force after Anaesthesia	*p*-Value
Landing	111 ± 28 kg	127 ± 34 kg	0.009
Midstance	265 ± 75 kg	307 ± 76 kg	<0.001
Breakover	135 ± 71 kg	170 ± 73 kg	0.001

3.2.4. Sound Limb before and after Anaesthesia

During all motion events of the stance phase, the vertical force on the sound limb decreased, corresponding to the increase in vertical force on the anaesthetised limb. The reduction was not significant during landing (−8%, $p = 0.06$) and midstance (−4%, $p = 0.1$), whereas a significant vertical force reduction was again observed during breakover (−13%, $p = 0.02$) (Table 7).

Table 7. Pairwise comparisons of the vertical force in kg on the sound limb before and after anaesthesia during landing, midstance, and breakover.

	Sound Limb: Vertical Force before Anaesthesia	Sound Limb: Vertical Force after Anaesthesia	*p*-Value
Landing	147 ± 45 kg	136 ± 35 kg	0.06
Midstance	332 ± 110 kg	318 ± 79 kg	0.1
Breakover	185 ± 87 kg	162 ± 63 kg	0.02

4. Discussion

To our knowledge, this study is the first to show that after positive diagnostic anaesthesia of a lame limb, the main increase in vertical force on the lame limb and the main decrease in vertical force on the sound limb occur mainly during the breakover phase.

The results of this study confirmed our first hypothesis that before diagnostic anaesthesia, significant differences in vertical force between lame and sound limbs are detectable with the Hoof™ System. At a trot, a significant vertical force reduction on the lame limb compared to the sound limb occurred during landing, midstance, and breakover. This would be expected, as it has been documented by previous studies [12–14,17]. Additionally, the biggest difference in vertical force between lame and sound limbs occurred during breakover, followed by landing, which leads to the speculation that bilateral vertical force in these two phases is more sensitive to the presence of pain than the vertical force acting during midstance phase, which displayed a smaller difference between sound and lame limbs. It has been assumed that during landing, high forces affect the limb as impact peaks, shock, and vibration [27] probably accentuate lameness caused by articular or osseous disorders and energy storing tendons, e.g., the superficial digital flexor tendon and the suspensory ligament [28]. In contrast, during breakover, high forces are transferred to the ground for limb propulsion immediately before the swing phase; in particular, tendons such as the deep digital flexor tendon and muscles and ligaments such as the accessory ligament of the deep digital flexor tendon are subject to high strain [29–31], so pain associated with lesions of these structures may become more obvious. Further studies are warranted to investigate whether changes in the stance phase vary depending on the nature of the painful structure. Another potential cause is that vertical force on the sound limb is increased during breakover in order to propulse the horse, reducing the vertical force on the lame limb during the following stance phase [12]. In return, the vertical force on the lame limb is decreased during breakover because of pain and in order to lower the head during the following stance phase of the sound limb. Subsequently, the difference in vertical force between both forelimbs is greatest during breakover. During midstance, there is pure vertical loading with no acceleration, thus reducing microvibrations and instabilities associated with landing or breakover [32]. This may explain our findings and a lesser contribution of the midstance phase to lameness. These findings need to be further investigated as the Hoof™ System allows discrimination between phases of locomotion, which may be further considered for lameness management strategies. The differentiation of which part of the stance phase is mostly affected may also complement the output of trunk-mounted IMU sensor-based lameness detection systems, which are incapable of such discrimination, as they only perform a comparison of motion symmetry into impact and push-off lameness representing the first and second half of the stance phase [33].

The second hypothesis referred to the changes seen after diagnostic anaesthesia and can also be supported by the results of this study since following diagnostic anaesthesia, the vertical force affecting the anaesthetised limb increased significantly, whereas the vertical force on the sound limb decreased, which led to a more symmetrical bilateral vertical force during all parts of the stance phase. This was expected, as a more symmetric movement resulting from a more even loading between lame and sound limbs occurs following positive diagnostic anaesthesia, as described by a previous study [17]. The Hoof™ System could detect and calculate these changes numerically, which makes the system potentially useful to monitor the effect of diagnostic anaesthesia objectively in a clinical setting.

Our final hypothesis stating that the maximum effect of diagnostic anaesthesia occurs during midstance has to be rejected, as we observed the maximum increase in vertical force on the anaesthetised limb during breakover. This result emphasises the meaning of this phase for equine locomotion and compensation mechanisms of painful processes in the limb [12,20,34] so that the loss of sensory feedback after diagnostic anaesthesia [35] might become more obvious during this part of the stance phase.

The observation that loading of front limbs was not completely symmetric after diagnostic anaesthesia was probably due to the different underlying pathologies inevitably leading to a variable improvement in lameness after diagnostic anaesthesia. In addition, it has been shown by pressure measuring that even sound horses may show an asymmetric bilateral loading [36]. This has to be considered in horses with mild lameness or those not responding to diagnostic anaesthesia. Theoretically, subtle hindlimb lameness becoming more dominant after positive anaesthesia of a lame front limb may also have influenced front limb loading through mechanisms of compensation [37]. To date, no threshold value for lameness has been found for the pressure mapping system used in the current study, as it has been described for body-mounted inertial sensor systems [9]. This will be necessary to support its routine clinical use. In a former study, it was reported that the Hoof™ System is not reliable compared to a force platform when being fixed with an equine hoof boot [22]. The reliability of mounting the sensor foils with adhesive tape was not evaluated in the current or former studies [18,19,21,34], which may have had an influence on the results. Another study could show reliability within but not between sessions when the sensor foils were attached with a glue-on shoe [38]. A potential cause for missing reliability between sessions could be sensel damage due to creases and delamination. Signs of disintegration, as described above, could also be observed in the current study, as measurements were performed on concrete flooring so that foam rubber and sensor foils were subject to abrasion, leading to the replacement of the sensors. To avoid the effect of humidity on sensor output, measurements took only place during dry weather [39].

In the current study, naturally lame horses were included, as we intended to investigate the system's performance under real clinical circumstances. In contrast to an experimental model, this study design inevitably led to several limitations. The variation in lameness degree between individuals may have influenced the results and may be responsible for the large standard deviation seen in our samples. It is possible that individuals with higher degrees of lameness had the highest impact on our results. Further investigations regarding the effect of the degree of lameness on the changes in the different parts of the stance phase will be of interest. Whether abnormal gait patterns caused by disorders of the musculoskeletal system not diagnosed in the current study would lead to other deviations from normal gait patterns during the different parts of the stance phase will have to be proved by including more cases classified by specific disorders in future studies. As described above, our standardised examination protocols concerned the position of the handler, timings following diagnostic anaesthesia, and the speed of horses. While the first two were easily controlled, we did not measure the speed of horses, which may have influenced the results, as time, force, and spatial parameters are velocity-dependent [40]. At higher speed, more horses with subtle lameness are assessed as sound during subjective lameness evaluation, whereas more prominent lameness becomes more visible with higher speed [41,42]. While sound horses likely trot at a constant speed [43], lame horses tend to increase their speed after diagnostic anaesthesia [42]. At the same time, peak vertical force increases with increasing velocities [40]. This might have contributed, along with the analgetic effect of the local anaesthetic [23], to the significant increase in vertical force on the lame limb after anaesthesia. On the other hand, this is a potential reason why the vertical force reduction on the sound limb after diagnostic anaesthesia is not significant. The influence of the handler position was considered low, as in a previous study on sound horses, the handler position did not affect limb loading and hoof balance [15].

5. Conclusions

Diagnostic anaesthesia eliminates the vertical force distribution asymmetries between both forelimbs seen in unilaterally lame horses as evaluated by pressure measurements. In lame horses, differences in vertical force distribution found between the components of the stance phase contribute to a better understanding of equine gait and facilitate customised shoeing solutions, with breakover being the most affected. Hoof™ System measurements can be used to evaluate symmetric loading at a trot and to evaluate the effect of diagnostic anaesthesia in a clinical setting. Further studies including a larger number of horses with specific disorders are warranted to confirm the results of the current study.

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Informed Consent Statement: Written informed consent was obtained from the owners of the animals involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest.

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4 Diskussion

4.1 Diskussion der Fragestellung

4.1.1 Beeinflussung des Druckmittelpunkt (centre of pressure, COP) Pfades nach Verlust der Propriozeption durch diagnostische Anästhesien

Ziel der eigenen Studie war die Untersuchung, ob diagnostische Anästhesien den COP-Pfad bei lahmheitsfreien Pferden beeinflussen oder ob er wiederholbar bleibt, um Rückschlüsse ziehen zu können, ob er als Parameter für objektive Lahmheitsuntersuchungen geeignet ist. Weitere Untersuchungen, ob sich der individuelle COP-Pfad bei Entwicklung einer Lahmheit verändert und für bestimmte Erkrankungen charakteristisch ist, scheinen sinnvoll, um ihn zur Früherkennung von Gangstörungen, objektiven Lahmheitsuntersuchungen oder Überprüfung von Therapieerfolgen einsetzen zu können. Eine frühere Studie zeigte, dass diagnostische Anästhesien bei lahmheitsfreien Pferden keinen Einfluss auf die vertikale Kraft und das klinische Gangbild haben (Keg et al. 1996), ebenso konnte eine weitere Studie zeigen, dass die Lastaufnahme sowie die Hufbalance (Zehe/Trachte, medial/lateral) von diagnostischen Anästhesien nicht beeinflusst werden (van de Water et al. 2016). Jedoch wurde bisher noch nicht die Beeinflussung des Druckmittelpunktes nach Verlust der Propriozeption durch diagnostische Anästhesien untersucht. Wilson et al. (2001) zeigten, dass sich der COP-Pfad, der für jedes Individuum und jede Gliedmaße individuell ausgeprägt ist (Nauwelaerts et al. 2017), bei gesunden Pferden und Pferden mit Strahlbeinerkrankungen unterscheidet. Der COP-Pfad wiederholt sich auch bei unilateral chronisch lahmen Pferden in hohem Maße und ist für jedes Pferd und jede Gliedmaße charakteristisch; die Variabilität des COP-Pfades erscheint zudem an der lahmen Gliedmaße im Vergleich zur lahmheitsfreien Gliedmaße verringert (Buser et al. 2023).

4.1.2 Auswirkung einer diagnostischen Anästhesie auf die bilaterale vertikale Druckverteilung bei Pferden mit einseitiger Lahmheit der Vordergliedmaßen während der Stützbeinphase mit Hilfe eines nicht-invasiven Druckmesssystems

Die vertikale Bodenreaktionskraft ist der sensitivste Parameter zur Bestimmung einer lahmen Gliedmaße (Keegan 2020) und in mehreren Studien wurde im Falle einer induzierten Lahmheit eine Verminderung der vertikalen Kraft bestätigt (Weishaupt et al. 2005, Weishaupt et al. 2006). Nach aktuellem Wissen der Autorin beschäftigt sich bisher jedoch nur eine Studie mit der Auswirkung der vertikalen Kraft nach positiver diagnostischer Anästhesie bei Strahlbeinerkrankungen (Bidwell et al. 2004). Die oben beschriebenen Studien haben jeweils eine stationäre Kraftmessplatte (force plates) sowie ein Laufband mit integriertem Kraftmesssystem (instrumented treadmill) verwendet. Das Hoof™ System bietet den Vorteil, dass es mobil ist und bei verschiedenen Bodenbeschaffenheiten verwendet werden kann (Hüppler et al. 2015). Ziel der Studie war es, zu untersuchen, ob das Hoof™ System Lahmheiten und Besserungen nach diagnostischen Anästhesien detektieren kann und somit als objektives Hilfsmittel zur Lahmheitsuntersuchung verwendet werden kann. Zusätzlich stellt das Hoof™ System die Druckverteilung unter dem Huf während der einzelnen Fußungsphasen dar.

4.2 Diskussion der Methode

4.2.1 Studienpopulation

In der ersten Veröffentlichung wurden aus einer vorberichtlich lahmheitsfreien Population von 50 Pferden 10 tatsächlich lahmheitsfreie Pferde in die Untersuchung eingeschlossen. Die vergleichsweise geringe Anzahl lahmheitsfreier Pferde deckt sich mit früheren Studien, in denen von 222 Pferden, die durch ihre Besitzer als lahmheitsfrei eingestuft wurden, 72,5 % eine Bewegungsasymmetrie zeigten, die oberhalb festgelegter Grenzwerte lag (Rhodin et al. 2017). Auch in zwei weiteren Studien wurden bei 53 % von 201 sowie 61 % von 23 Pferden, die von ihren Besitzern als lahmheitsfrei eingestuft wurden, mittels objektiver Messungen Bewegungsasymmetrien festgestellt (Rhodin et al. 2016, Pfau et al. 2016). Daraus lässt sich schlussfolgern, dass insbesondere Gangstörungen geringeren Grades vielfach von tiermedizinischen Laien (Eigentümer, Besitzer) nicht erkannt oder als nicht relevant eingestuft wurden. So wurde in einer aktuellen Untersuchung bei mindestens 88 % der lahmheitsfreien Pferde eine Bewegungsasymmetrie des Widerrists zwischen -10% und 7% festgestellt und mindestens 86 % der gesunden Pferde wiesen eine Asymmetrie der Beckenbewegung zwischen -7 % und 18 % auf (Macaire et al. 2022). Eine Abgrenzung zwischen einer klinisch relevanten und einer nicht beeinträchtigenden Bewegungsasymmetrie geringen Ausmaßes ist somit im Einzelfall nicht immer sicher möglich. Dies deutet auf eine Dunkelziffer unerkannter, aber relevanter Lahmheiten hin.

Auch die subjektive Beurteilung des Gangbildes durch Tierärzte ist vor allem bei geringgradigen Lahmheiten fehleranfällig (Keegan et al. 2010), weshalb in dieser Studie zur Auswahl der lahmheitsfreien Pferde zusätzlich ein validiertes objektives System zu Hilfe genommen wurde (Lameness Locator®) (Keegan et al. 2011, Keegan et al. 2012, McCracken et al. 2012). Mittels IMU-Sensoren, welche auf Genick, Kruppe und an rechter Vordergliedmaße befestigt werden, wird die Asymmetrie der Kopf- und Kruppenbewegung gemessen. Pferde mit einer Differenz der vertikalen Kopfbewegung < 6 mm und einer vertikalen Symmetrie der Beckenbewegung < 3 mm werden als lahmheitsfrei eingestuft (Ros 2021, Equinosis 2016). Die geringe Anzahl an Pferden in der vorliegenden Studie hat einen möglichen Einfluss auf die Ergebnisse, welche mittels einer Studie mit größerem Patientengut überprüft werden sollten.

Ziel der zweiten Studie war es, den Effekt diagnostischer Anästhesien mittels Hoof™ System objektiv zu beurteilen sowie dessen Einfluss auf die unterschiedlichen Fußungsphasen zu überprüfen. Daher wurden alle geeigneten Pferde mit Vorderhandlahmheit eingeschlossen, die in der Klinik für Pferde (Chirurgie und Orthopädie) des Fachbereichs Veterinärmedizin der Justus-Liebig-Universität Gießen vorgestellt wurden, und zwar unabhängig von Rasse, Alter, Geschlecht, Lahmheitsgrad und letztendlicher Lahmheitsursache. Diese Faktoren hatten möglicherweise einen Einfluss auf die Ergebnisse, da der variable Lahmheitsgrad einzelner Pferde zu einer großen Standardabweichung der Stichproben führte und somit Pferde mit höheren Lahmheitsgraden den größten Einfluss auf die Ergebnisse hatten. Ebenso besteht die Möglichkeit, dass die unterschiedlichen Lahmheitsursachen einen individuellen Einfluss auf die einzelnen Fußungsphasen haben, da sich Erkrankungen einzelner Strukturen unterschiedlich stark in den einzelnen Fußungsphasen ausprägen können (Clayton et al. 1998, Page et al. 2002, Clayton et al. 1987, Clayton et al. 1990).

Die Pferde wurden in den Studien dieser Arbeit an der Hand vorgeführt. Dabei wurde konsequent auf die Einhaltung einer möglichst konstanten Geschwindigkeit geachtet. Da die Geschwindigkeit Auswirkungen auf die Bodenreaktionskraft hat (Weishaupt et al. 2010, Starke et al. 2013, Peham et al. 2000, Degueurce et al. 1997), wäre für zukünftige Studien die objektive Überwachung der Geschwindigkeit mit entsprechenden technischen Hilfsmitteln wie IMUs oder GPS ratsam (Witte u. Wilson 2004, Morrice-West et al. 2021). Alternativ bietet sich die Verwendung eines Laufbandes für Pferde an (Weishaupt et al. 2010), welches in der vorliegenden Arbeit nicht zur Verfügung stand und wiederum andere Nachteile wie z.B. einen höheren Reibungskoeffizienten zwischen Huf und Untergrund mit sich bringt und zu Veränderungen des Gangbildes im Vergleich zu einer herkömmlichen Vorführbahn führt (Buchner et al. 1994).

4.2.2 Hoof™ System (auch im Vergleich zu anderen technischen Mitteln)

Mit dem verwendeten Hoof™ System wurden vertikale Bodendrücke erfasst. Die Bodenreaktionskraft teilt sich hingegen in eine für die Ganganalyse bedeutendste vertikale, aber auch eine transversale und eine sagittale Komponente (Keegan 2020). Grundsätzlich wurde zwar durch den direkten und simultanen Vergleich von im Untergrund eingelassenen Druck- und Kraftmessplatten weitreichende Korrelationen zwischen den Parametern Bodenreaktionskraft und Hufdruck belegt (Oosterlinck et al. 2010), allerdings erlaubt das in der vorliegenden Arbeit verwendeten System keinerlei Aussage über die sagittalen und transversalen Komponenten der Bodenreaktionskraft.

Da die Messung von Bodenreaktionskräften (kinetisches Verfahren) als Goldstandard zur Bestimmung von Lahmheiten gilt (Roepstorff et al. 2022), allerdings die Verfügbarkeit von in den Boden integrierten Druckmessplatten oder instrumentierten Laufbändern sehr begrenzt ist, bietet das verwendete Hoof™ System den großen Vorteil, dass es an der Unterseite des Probandenhufes angebracht werden kann und eine vollflächige Erfassung des Druckprofils erlaubt (Hüppler et al. 2015). Bereits seit den 1950er Jahren wurden wiederholt Versuche unternommen, Bodenreaktionskräfte von Pferden mit Kraft- oder Druckmesseinrichtungen, die am Huf des Probanden befestigt sind, zu bestimmen: dazu gehören Kraftmess-Hufeisen (Force Shoes) (Chateau et al. 2009) und Kraft- bzw. Druckmess-Hufschuhe (Force Boots) (Roepstorff u. Dremovo 1993), die ebenfalls z.T. durch die Kombination von verfügbaren Hufschuhsystemen mit Druckmessmatten als Prototypen hergestellt wurden. Das Anbringen des Hoof™ Systems am Huf hat sich in der vorliegenden Arbeit als verhältnismäßig aufwendig, verschleiß- und störanfällig erwiesen. Neben dem Verschleiß und der begrenzten Haltbarkeit der Druckmessmatten, insbesondere bei beschlagenen Pferden, fiel insbesondere die kabelbasierte Datenübertragung entlang der Gliedmaße negativ ins Gewicht und erforderte stets equine Probanden mit der nötigen Kooperationsbereitschaft. Für zukünftige Studien und eine weitere Verbreitung der diagnostisch wertvollen vertikalen Hufdruck- bzw. Bodenreaktionskraftmessung wäre dementsprechend ein robustes und langlebiges System mit kabelloser Übertragung der Messdaten in Echtzeit wünschenswert.

Es wurden zwar von verschiedenen Arbeitsgruppen Versuche unternommen, das Hoof™ System am Pferdehuf zu validieren (Lange et al. 2012), allerdings ist keine systematische und umfängliche Validierung des Systems in der Literatur hinterlegt. Diesbezüglich wäre ein Vergleich zwischen Kraftmessdaten, die mit einer im Untergrund integrierten Kraftmessplatte gewonnen werden, sowie den vertikalen Druckmessdaten des Hoof™ Systems erstrebenswert (Oosterlinck et al. 2010).

Bei der Datenauswertung konnte mit dem verfügbaren System der vertikale Druck auf den Untergrund sowie der Druckmittelpunkt im Verlauf des Bewegungszyklus gemessen werden. Die exakte Bestimmung der einzelnen Stützbeinphasen war allerdings allein aufgrund dieser Daten nicht möglich und hätte noch weitere Parameter erfordert, wie sie z.B. mit Hilfe einer am Huf befestigten IMU abrufbar wären. Eine Kombination aus Lagesensorik einerseits und Druck-/Kraftmesssensorik andererseits wäre für zukünftige Untersuchungen von Interesse. Zudem wäre die Berechnung des Impulses, der sich aus der Fläche unter der Kurve des zeitlichen Verlaufes der vertikalen Bodenreaktionskraft ergibt, zur Charakterisierung von Gangstörungen von Bedeutung.

Wenngleich die meisten Gangstörungen bei Pferden erst in der Gangart Trab sichtbar in Erscheinung treten, bietet die Erfassung des vertikalen Hufdrucks, z.B. mit dem Hoof^{TM} System, den großen Vorteil, dass sie im Gegensatz zu den meisten sensorbasierten kinematischen Verfahren (z.B. Lameness Locator®, Equinosis®) auch im Schritt verlässliche Daten liefert (Al Naem et al. 2021, Hüppler et al. 2015). Dies fällt bei der Früherkennung von Gangstörungen, wie auch bei der Überwachung huforthopädischer Maßnahmen hilfreich ins Gewicht.

Um die objektive Beurteilung des Gangbildes einer größeren Gruppe an Untersuchern zugänglich zu machen und mögliche Asymmetrien des Gangbildes frühzeitig zu erkennen, wurde ein System entwickelt, welches das Gangbild auf Grundlage von Videos, die mit einem Smartphone angefertigt wurden, markerlos ohne IMU-Sensoren analysiert (Lawin et al. 2023). Die einfache Anwendung auf einem Smartphone bietet eine örtlich flexible und kostengünstige Gangbildanalyse (Lawin et al. 2023).

4.3 Diskussion der Ergebnisse

In der ersten Studie wurden die individuellen COP (center of pressure) Pfade beider Vordergliedmaßen vor und nach uni- und bilateraler mittlerer Palmarnervenanästhesie untersucht: der individuelle COP-Pfad ist für jedes Pferd und jede Gliedmaße wiederholbar und zeigte keine signifikante Variabilität zwischen den einzelnen Tritten. Der Initialkontakt sowie der COP-Pfad während der Hauptstützphase und während des Abfußens blieb vor und nach uni- und bilateraler Anästhesie gleich. Das Ergebnis vor Anästhesie deckt sich mit 2 früheren Untersuchungen (Nauwelearts et al. 2017, Buser et al. 2023). Auf unebenem oder steinigem Boden ist die Propriozeption des Hufes ein wichtiger Teil des sensorischen Feedback-Mechanismus, um Verletzungen zu vermeiden (Bowker et al. 1995). In der eigenen Studie wurde eine harte, ebene Vorführbahn zur Ermittlung der Daten verwendet, auf der die Pferde ein rhythmisches und wiederholtes Gangbild zeigten. Aus diesem Grund spielte die Sensorik am Huf vermutlich eine untergeordnete Rolle. Die Erzeugung des Bewegungsmusters in der Stütz- und Hangbeinphase wird vermutlich hauptsächlich durch zentrale

Mustergeneratoren (Central Pattern Generators, CPG) im Gehirn und Rückenmark bestimmt (Guertin 2012), weshalb der Verlust der Propriozeption durch diagnostische Anästhesien wahrscheinlich keinen Einfluss auf den COP-Pfad hatte. Weitere Untersuchungen des COP-Pfades zur Prüfung der Fragen, ob sich dieser im Rahmen der Lahmheitsentstehung bei Pferden verändert oder bei bestimmten Erkrankungen charakteristisch ist und ob diese Effekte sich durch diagnostische Anästhesien neutralisieren lassen, wären zur Weiterentwicklung der objektiven Ganganalyse von Bedeutung.

Die zweite Studie bestätigte, dass das Hoof^{TM} Sytem nicht nur zur Detektion von Lahmheiten durch verminderten vertikalen Druck genutzt werden kann, sondern auch zur Überprüfung diagnostischer Anästhesien und somit als Hilfsmittel bei objektiven Lahmheitsuntersuchungen geeignet ist: vor der diagnostischen Anästhesie war der vertikale Druck an der lahmen Gliedmaße im Vergleich zur gesunden Gliedmaße während der Landung (-25%, $p < 0{,}001$), der Hauptstützphase (-20%, $p < 0{,}001$) und dem Abfußen (-27%, $p < 0{,}001$) signifikant reduziert. Die Ergebnisse weisen darauf hin, dass der bilaterale vertikale Druck während des Abfußens und Auffußens sensitiver auf Schmerzen reagiert als der vertikale Druck in der Hauptstützphase. Eine Vermutung ist, dass während des Auffußens hohe Kräfte auf die Gliedmaße einwirken, da Aufprallspitzen, Stöße und Vibrationen (Barrey et al. 1991) wahrscheinlich Lahmheiten verstärken, die durch Gelenk- oder Knochenerkrankungen sowie Erkrankungen der energiespeichernden Sehnen, z. B. der oberflächlichen Beugesehne und des Unterstützungsbandes hervorgerufen werden (Clayton et al. 1998). Im Gegensatz dazu werden beim Abfußen unmittelbar vor der Hangbeinphase hohe Kräfte zum Vortrieb der Gliedmaßen auf den Boden übertragen; insbesondere Sehnen wie die tiefe Beugesehne sowie Muskeln und Bänder wie das Unterstützungsband der tiefen Beugesehne werden stark beansprucht (Page et al. 2002, Clayton 1987, Clayton et al. 1990). Während der Hauptstützphase findet eine rein vertikale Belastung ohne Beschleunigung statt, wodurch Mikrovibrationen und Instabilitäten im Zusammenhang mit dem Auf- oder Abfußen reduziert werden (Thomason u. Peterson 2008). Weitere Studien sind erforderlich, um zu untersuchen, ob die Veränderungen in der Stützbeinphase von der Art der schmerzhaften Struktur abhängen.

Nach der Anästhesie war der Unterschied zwischen den beiden Vorderbeinen in allen Phasen nicht mehr signifikant: der vertikale Druck nahm an der anästhesierten Gliedmaße deutlich zu, während der vertikale Druck an der gesunden Gliedmaße abnahm, was zu einer symmetrischeren bilateralen vertikalen Druckverteilung in allen 3 Phasen der Stützbeinphase führte. Dies steht im Einklang mit einer anderen Untersuchung, die ausschließlich Strahlbeinerkrankungen untersucht hat (Bidwell et al. 2004). Da in unserer Studie Pferde mit unterschiedlichen orthopädischen Erkrankungen eingeschlossen wurden, konnten wir zeigen, dass dieses Phänomen auch bei verschiedenen Lahmheitsursachen zum Tragen kommt.

Der vertikale Druck an der lahmen Gliedmaße nahm nach positiver Anästhesie während der gesamten Stützbeinphase signifikant zu, wobei die Phase des Abfußens am stärksten betroffen war (+27%, p = 0,001). Dies deckt sich mit früheren Studien, in denen Auswirkungen orthopädischer Erkrankungen auf die Abfußphase festgestellt wurden: eine zeitlich verlängerte Abfußphase kann auf Erkrankungen des Bewegungsapparates hinweisen (Tijssen et al. 2020), bei Pferden mit Hufrehe tritt die größte vertikale Kraft während des Abfußens auf (Al Naem et al. 2021).

4.4 Ausblick

In der vorliegenden Arbeit wurde das Druckmessystem lediglich an den Vordergliedmaßen angewendet, so dass die Auswirkung der festgestellten Gangstörungen der Vordergliedmaßen auf das Druckmessbild der Hinterhufe nicht erfasst werden konnte. Dies wäre für zukünftige Studien zur Erfassung von Schein- bzw. Mehrfachlahmheiten von großem Interesse, würde jedoch eine technisch einfachere Instrumentierung des Probanden erfordern.

Schlussfolgernd wäre für die Zukunft ein einfach anwendbares und validiertes System zur Bestimmung des vertikalen Drucks - idealerweise der Bodenreaktionskraft in 3 Ebenen - mit kabelloser Echtzeitübertragung erstrebenswert, das vorteilhafterweise eine in Hufnähe befestigte inertiale Messeinheit (IMU) aufweist.

Wenn zudem gleichzeitig am Körper (z.B. Genick, Hals, Rücken, Becken) von Pferden mit Gangstörungen ein IMU basiertes System angebracht oder ein markerloses optisches System Anwendung finden würde, könnten die diagnostischen Vorteile kinetischer Systeme und kinematischer Systeme systematisch miteinander verglichen und gegebenenfalls sinnvoll kombiniert werden, um bestimmte krankheitstypische Bewegungsabläufe genauer zu charakterisieren.

Ob möglicherweise zukünftig eine Häufung spezifischer COP- oder Druck-/Kraftmuster bei bestimmten Erkrankungen feststellbar sein wird, kann nur an einer großen Zahl von Probanden mit großen Datenmengen und unter Hinzuziehung künstlicher neuronaler Netzwerke verlässlich überprüft werden.

5 Zusammenfassung

Die frühe Erkennung von Lahmheiten bei Pferden, eine exakte Diagnose sowie angemessene Behandlung sind aus tierethischer und wirtschaftlicher Sicht sehr bedeutsam, jedoch ist die subjektive Bewertung eines lahmenden Pferdes durch visuelle Beurteilung fehleranfällig. Um die Untersuchung zu objektivieren, stehen einerseits kinematische Methoden zur Erfassung der Position von Kopf, Becken, Widerrist zur Verfügung. Kinetische Untersuchungen basieren auf der Messung der Bodenreaktionskraft oder des Drucks der Hufe auf den Untergrund. Die Ermittlung des Druckmittelpunktes (center of pressure, COP) und seines Verlaufes (COP-Pfad) sind im Rahmen objektiver Lahmheitsuntersuchungen noch relativ unerforscht.

Ziel der ersten Studie war es zu ermitteln, welche Auswirkung der kurzfristige Verlust der Propriozeption durch eine perineurale Leitungsanästhesie auf den individuellen Verlauf des Druckmittelpunktes bei lahmheitsfreien Pferden im Trab hat. Zehn Pferde wurden mit Hilfe inertialer Messeinheiten (Lameness Locator®, Equinosis®) objektiv als lahmheitsfrei eingestuft. Die individuellen COP-Pfade beider Vorderhufe wurden vor und nach uni- und bilateraler mittlerer Palmarnervenanästhesie mit Hilfe eines mobilen Druckmesssystems (Hoof^{TM} System, Fa. TekScan) bestimmt. Der Verlauf des COP vom ersten Bodenkontakt des Hufes über die Hauptstützbeinphase bis zum Abfußen sowie die Variabilität zwischen den Schritten wurden für jedes Pferd und jede Extremität deskriptiv ausgewertet. Für jedes Pferd und jede Gliedmaße wurde eine hohe Wiederholbarkeit des individuellen COP-Verlaufs während der Stützbeinphase ohne signifikante Variabilität zwischen den einzelnen Schritten nachgewiesen. Der Initialkontakt sowie der COP-Pfad während der Hauptstützphase und während des Abfußens blieben vor und nach uni- und bilateraler Anästhesie gleich. Da die mittlere Palmarnervenanästhesie keinen Einfluss auf den Verlauf des COP-Pfades während der Stützbeinphase hatte, eignet sich dieser potenziell als Untersuchungsparameter bei Lahmheitsuntersuchungen.

Die vertikale Bodenreaktionskraft gilt als Goldstandard bei der Erkennung von Lahmheiten. In der Literatur finden sich nur wenige klinische kinetische Untersuchungen zur Wirkung diagnostischer Anästhesien auf die einzelnen Phasen der Stützbeinphase bei lahmen Pferden.

Deshalb wurden in der zweiten Studie vierzehn Pferde mit einseitiger Lahmheit der Vordergliedmaßen mit dem Hoof™ System im Trab untersucht, um die vertikale Druckverteilung (in kg) an beiden Vorderhufen vor und nach positiver diagnostischer Anästhesie während des Auffußens, der Hauptstützphase und des Abfußens zu bewerten. Für die statistische Analyse wurde eine Kovarianzanalyse mit wiederholten Messungen in Bezug auf die Gliedmaße (lahm/gesund) sowie die Anästhesie (vor/nach) und das Körpergewicht durchgeführt. Für die gesamte Stützbeinphase zeigte sich eine signifikante Interaktion zwischen den Faktoren Gliedmaße und Anästhesie. Vor der diagnostischen Anästhesie war der vertikale Druck an der lahmen Gliedmaße im Vergleich zur gesunden Gliedmaße während des Auffußens (-25 %, p < 0,001), der Hauptstützphase (-20 %, p < 0,001) und des Abfußens (-27 %, p < 0,001) signifikant reduziert. Nach der Anästhesie war der Unterschied zwischen den beiden Vorderbeinen in allen Phasen nicht mehr signifikant. Der vertikale Druck an der lahmen Gliedmaße nahm nach positiver diagnostischer Anästhesie während der gesamten Stützbeinphase signifikant zu, wobei das Abfußen am stärksten betroffen war (+27%, p = 0,001).

Zusammenfassend können Druckmessungen mit dem Hoof™ System verwendet werden, um die Wirkung einer diagnostischen Anästhesie im Rahmen einer Lahmheitsuntersuchung objektiv auszuwerten. Schmerzbedingte vertikale Druckasymmetrien werden nach einer positiven diagnostischen Anästhesie neutralisiert.

6 Summary

Early recognition, precise diagnosis and appropriate treatment of equine lameness are important from an ethical and economic point of view, but subjective visual assessment of lameness is affected by errors. In order to objectify the examination, kinematic methods are available to record the position of the head, pelvis and withers. By contrast, kinetic examinations are based on the measurement of the ground reaction force or the pressure of the hooves on the ground. The determination of the center of pressure (COP) and its path are still relatively unexplored in the context of objective lameness investigations.

The aim of the first study was to determine the effect of short-term loss of proprioception due to perineural anaesthesia on the individual COP path in non-lame horses at the trot. Ten horses were objectively classified as free of lameness using a commercial inertial measurement unit-based system (Lameness Locator®, Equinosis®). Individual COP paths of both front hooves were determined before and after unilateral and bilateral middle palmar nerve anaesthesia using a mobile pressure measurement system (Hoof™ System, TekScan). The COP path from landing through midstance to breakover and the variability between steps were descriptively evaluated for each horse and limb.

High repeatability of the individual COP-path during the stance phase was demonstrated for each horse and each limb without significant variability between steps. The initial contact as well as the COP path during midstance and breakover remained the same before and after unilateral and bilateral anaesthesia. Perineural anaesthesia at the level of the fetlock had no effect on the COP path during the whole stance phase, making it potentially suitable as a consistent investigative parameter even under the effect of diagnostic anaesthesia.

Vertical ground reaction force is considered as gold standard in the detection of lameness. Until now, few clinical kinetic studies have focused on the effect of diagnostic anaesthesia during the different stance phases in lame horses. Therefore, in the second study, fourteen horses with unilateral forelimb lameness were examined with the Hoof™ System at trot to evaluate the vertical force distribution (in kg) on both forelimbs before and after positive diagnostic anaesthesia during landing, midstance and breakover. For statistical evaluation, an

analysis of covariance was performed with repeated measures in relation to limb (lame/sound) as well as anaesthesia (before/after) and body weight. For all stance phases there was a significant interaction between the factors limb and anaesthesia. Vertical force on the lame limb was significantly reduced compared to the sound limb during landing (-25 %, $p < 0.001$), midstance (-20 %, $p < 0.001$) and breakover (-27 %, $p < 0.001$) before diagnostic anaesthesia. During the whole stance phase after anaesthesia, the difference between the two forelimbs was no longer significant. Vertical force on lame limb increased significantly throughout stance after positive diagnostic anaesthesia, the main increase occurred during breakover (+27%, $p = 0.001$).

In summary, pressure measurements with the Hoof™ System are applicable to objectively evaluate the effect of diagnostic anaesthesia during lameness examination. Vertical force asymmetries due to pain are neutralised after positive diagnostic anaesthesia.

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8 Publikationsverzeichnis

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Hagen J, Geburek F, Kathrinaki V, Naem MA, Roecken M, Hoffmann J. Effect of Perineural Anesthesia on the Centre of Pressure (COP) Path During Stance Phase at Trot in Sound Horses. J Equine Vet Sci. 2021 Jun;101:103429. doi: 10.1016/j.jevs.2021.103429

Hoffmann JR, Geburek F, Hagen J, Büttner K, Cruz AM, Röcken M. Bilateral Change in Vertical Hoof Force Distribution in Horses with Unilateral Forelimb Lameness before and after Successful Diagnostic Anaesthesia. Animals. 2022; 12(18):2485. https://doi.org/10.3390/ani12182485

(Teil-) Ergebnisse dieser Dissertation wurden auf folgenden Fachkongressen präsentiert:

Hoffmann J, Al Naem M, Hagen J, Röcken M. Lahmheitsassoziierte Änderungen des Druckmessbildes orthopädischer Patienten – Fallbeispiele. In: Leipziger Blaue Hefte.
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9 Erklärung

Ich erkläre:

Ich habe die vorgelegte Dissertation selbständig und ohne unerlaubte fremde Hilfe und nur mit den Hilfen angefertigt, die ich in der Dissertation angegeben habe. Alle Textstellen, die wörtlich oder sinngemäß aus veröffentlichten oder nicht veröffentlichten Schriften entnommen sind, und alle Angaben, die auf mündlichen Auskünften beruhen, sind als solche kenntlich gemacht. Bei den von mir durchgeführten und in der Dissertation erwähnten Untersuchungen habe ich die Grundsätze guter wissenschaftlicher Praxis, wie sie in der "Satzung der Justus-Liebig-Universität Gießen zur Sicherung guter wissenschaftlicher Praxis" niedergelegt sind, eingehalten.

Gießen, den 05.10.2023

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