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Trunk kinematics and limb movement of horses walking backwards and forwards in hand and lifting a single limb

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ABSTRACT

Equine physiotherapy commonly includes basic exercises such as walking backward (BW) and voluntary lifting of single limbs (SLL), but trunk movements during these have not been studied. In order to compare the trunk kinematics during BW and SLL with forward walking (FW), nine horses were measured in FW, BW and during SLL triggered by tactile cue. Kinematics were obtained from skin markers captured by ten high-speed video cameras. Trunk angles were calculated in sagittal and horizontal planes from withers, dorsal to spinous processes of the 16th thoracic vertebra (T16), 2nd and 4th sacral vertebrae (S2, S4), WT16S2 and T16S2S4 respectively. From the hooves, maximum hoof height during swing phase and horizontal distance between hoof and median body plane during swing and stance phases were determined.

Dorsoventral range of motion (ROM) and maximum flexion of WT16S2 was significantly larger in BW than in FW, while laterolateral ROM was significantly smaller during hindlimb swing phase in BW and SLL than in FW. In contrast, dorsoventral ROM of T16S2S4 was significantly smaller during stance and swing phases of hindlimbs in BW compared to FW, and throughout the movement. During forelimb swing phase, T16S2S4 ROM was significantly larger in BW than SLL. Hindhoof height in SLL was significantly higher than in FW. Distance between median body plane and hooves was significantly larger in BW than in FW, and significantly larger in BW than in SLL for hindlimb swing phase. In BW, increased lumbosacral stabilisation and the larger area of support created by fore- and hindlimbs may represent a strategy to enhance body stabilisation, as BW entails some insecurity.

Introduction

The use and awareness of physiotherapy as a proactive and reactive treatment programme within equestrian sport appears to have increased over the last 30 years, and a variety of exercises aiming at improving trunk muscle control and volume are recommended (e.g., Mooij et al., 2013; De Oliveira et al., 2015; Clayton, 2016; Nankervis et al., 2016; Pfau et al., 2017; Shakeshaft and Tabor, 2020; Shaw et al., 2021). In equine physiotherapy, increasing spinal range of motion and inducing thoracolumbar flexion constitute important goals (Shakeshaft and Tabor, 2020). Walking forward (FW) and backing up (BW) on level ground are basic exercises for ambulatory horses, where the underlying condition does not preclude them from carrying their body mass (Parelli et al., 1993; Paulekas and Haussler, 2009; Olsen et al., 2014). If ambulation is a risk, such as in horses with neurological dysfunction supported in a sling, or with long bone fracture, equines may still do a minimum level of physiotherapeutic exercise. Encouraging the horse by tactile cue to lift single limbs (SLL) can be done standing in variably balanced stance positions (square and non-square), and varying head and neck positions as well as surfaces. This aims at increasing proprioception and neuromuscular control (Clayton, 2016).

Body use in FW and BW is not as well documented in horses as it is in humans (Nadeau et al., 2003; Lee et al., 2013), with one study reporting hindlimb movement and pelvic angle but not trunk data of horses in BW (Seino et al., 2019). The neurological relevance of BW and SLLs is shown in horses affected by shivering, a neurological disorder (Draper et al.,

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2015; Seino et al., 2019). Compared to healthy horses, horses with shivering showed shorter stride lengths when FW and BW and increased hindlimb hoof elevation in both movement directions and during hindlimb SLL, as well as a wider hindlimb stance (Seino et al., 2019).

Kinematics of the equine trunk is reported in walk, trot, and canter, on curved lines and over jumps (e.g., Audigié et al., 1999; Faber et al., 2000; Licka et al., 2001; Gómez Alvarez et al., 2009; Johnson and Moore-Colyer, 2009; Walker et al., 2018; Byström et al., 2021). During FW on a treadmill, lateral angle of the vertebral column was maximal in the lumbar region while dorsoventral movement was biggest at the sacrum (Licka et al., 2001), and lateral bending of the lumbar region decreased during trotting on a treadmill compared to overground (Gómez Alvarez et al., 2009). As the need for research into physiotherapeutic and rehabilitative methods is undisputed, the present study set out to compare trunk movements and lateromedial position of limbs associated with FW and BW as well as SLLs at stance in healthy horses. The following hypotheses will be investigated: Range of back movement is smaller in BW than in FW. Limbs will be lifted higher and placed more medially in FW and SLL than in BW.

Materials and methods

The study was conducted at the University of Veterinary Medicine, Vienna. All procedures were discussed and approved by the Institutional Ethics and Animal Welfare Committee in accordance with GSP guidelines and national legislation (ETK-04/07/2016, date of approval 04 July 2016).

Horses

Nine horses (age: 4–17 years (13 ± 5 years); body mass: 477–624 kg (558 ± 45 kg); mean height at the withers: 1.58 (± 0.09) m; five mares, four geldings; five Standardbreds, two Warmbloods, two Haflingers) were included in this study. Prior to data collection, horses had been part of the university teaching herd for a minimum of 1.5 years and were not used for riding. Each horse underwent a clinical examination to rule out pathologies relevant to the movements assessed. They were trained to do BW in hand and SLL on tactile cue willingly. Before data collection, horses were evaluated in walk and trot on firm ground by an experienced clinician (T.F.L.) and lameness greater than 2/5 in trot and 1/5 in walk (AAEP Lameness Scale) led to exclusion from the study. No horse had displayed any clinical signs of neurological disease during the university ownership, nor were these noted during preparation prior to and/or during data collection. All horses were unshod, and hooves were trimmed by a licensed farrier one week prior to data collection.

Marker placement

Spherical retro-reflective skin markers were affixed on the skin over the dorsal spinous processes of the withers (dorsal to the highest dorsal spinous processes (Wm) and one on either side (Wl, Wr)), of the 16th thoracic vertebra (T16), of the 2nd (S2) and 4th (S4) sacral vertebrae, and on the lateral hoof wall of all four hooves. Additional markers were placed on the head and neck, as well as on metacarpi and metatarsi; these were not considered in this study. Ten cameras (Eagle Digital Real Time System, Motion Analysis Corporation) recorded 3-dimensional (3D) movement data at 120 Hz. A right-handed Cartesian coordinate system was used; x-axis was parallel and horizontal along the walkway, y-axis was horizontal and perpendicular to x, and the z-axis was vertical. During measurements video cameras recorded from both sides at about 3 m from the horse for additional information.

Data collection

The horses were controlled from the front with a rope attached to the halter by one investigator (I.D.J.). No tension was applied on the lead

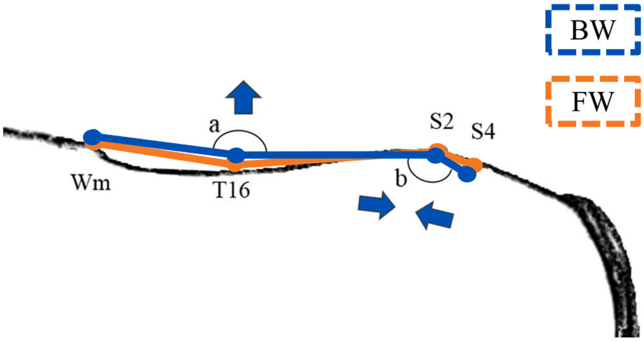

Fig. 1. Back angles of the sagittal plane measured at two sites of the vertebral column; (a) dorsal angle between markers dorsal to spinous processes at the median line of the withers (Wm), 16th thoracic vertebra (T16), and 2nd sacral vertebra (S2); (b) ventral angle between markers dorsal to spinous processes at T16, S2, and 4th sacral vertebra (S4). Adaptations of both angles during backward walk (BW) are shown in blue: compared to forward walk (FW; orange) (a) increases due to lifting of the back, (b) decreases due to pronounced lumbosacral flexion.

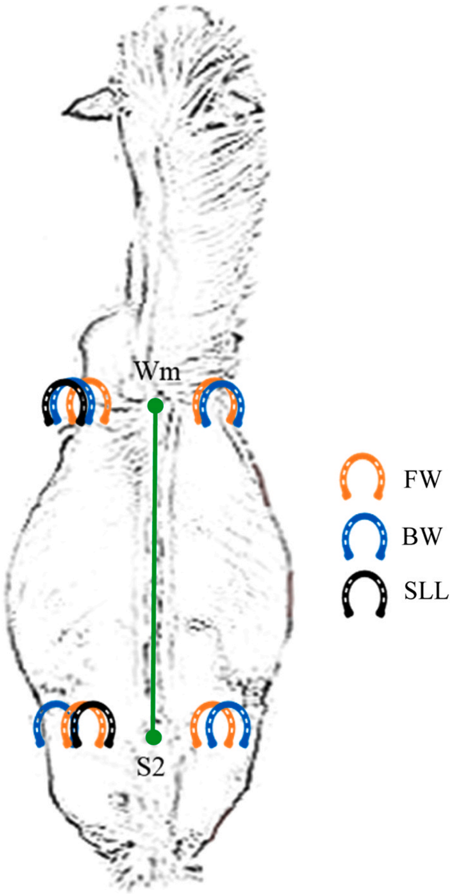

Fig. 2. Horse viewed from above; green line represents the median body plane, connecting markers at mid-wither (Wm) and 2nd sacral vertebra (S2). Orange hoof prints, median position of fore and hind hooves during forward walk (FW); Blue hoof prints, median position of fore and hind hooves during backward walk (BW); Black hoof prints, median position of fore and hind hooves during single limb lift (SLL). Hoof prints on the left body side represent results of five horses (forelimbs) and six horses (hindlimbs), comparing SLLs to swing phases of FW and BW. Hoof prints on the right body side represent results of nine horses, comparing stance phases of FW and BW. Note the larger area of support created by fore- and hindlimbs during BW compared to FW.

rope during FW and BW. Each horse was measured on level, hard rubber surface. Data was recorded in backward walk (BW), forward walk (FW), both at self-selected speed, and during lifting of single limbs (SLL). Measurements started at stance, followed by BW, stance, and FW. Trials of 10 s each were repeated twice in the same order to obtain three recordings per movement direction per horse. Then SLL was measured for 5 s with horses at stance encouraged by tactile cue to actively lift each limb without manual support. In a correct SLL trial, one limb was lifted from stance and placed back on the ground without initiating locomotion before the recording stopped.

Data processing

Kinematic software (Cortex-64 5.3.1., Motion Analysis Corporation) was used to smooth data with a 5 Hz cut-off Butterworth low-pass filter. Further processing in Microsoft Excel 2021 included hoof marker z-axis data normalisation to the baseline. Hoof x-axis acceleration exceeding $0.12\ \mathrm{m/s^2}$ was defined as swing phase. Videos were evaluated for quality control. Values on the y-axis were normalised to the spine aligned to the x-axis at quiet square stance. Angles were calculated between markers Wm, T16, S2 and S4 (WmT16S2 and T16S2S4, respectively), with lateral angles calculated from x and y coordinates (L-angWmT16S2 and L-angT16S2S4, respectively), and flexion-extension angles from x and z coordinates as dorsal angle of WT16S2 (D-angWmT16S2) and the ventral angle of T16S2S4 (V-angT16S2S4) (Fig. 1). Angles are reported throughout the movement (corresponding to one to three motion cycles, beginning with lifting of the movement-initiating limb, and ending on landing of the last limb) and for swing and stance phases of each limb in BW and FW, as well as for the swing phase of SLLs. Minimum, median, and maximum values, as well as angular range of motion (ROM) were calculated for each of the phases listed above. If a movement was presented more than once, mean values of the resulting parameters were calculated for each horse for comparisons between BW, FW, and SLL.

All distances were converted to percent of each horse’s height at its withers (%hw) and summary statistics were calculated. In both stance and swing phases, the minimum (and maximum) distance between hoof and median body plane (DistMBPH) was determined (Fig. 2), equivalent to the most medial (lateral) position of the moving limb during swing phase and the most lateral (medial) position of the moving median body plane (vector Wm-S2) over the hoof at stance. Maximum vertical height reached by the hoof (MaxH) during swing phases of FW, BW, and SLLs from hoof marker z-axis after normalisation to the baseline is reported with its time of occurrence determined in percent of the duration of each swing phase (%dsw).

Statistical analysis

Statistical analysis (IBM SPSS Statistics version 27) included Shapiro-Wilk normality tests prior to further analysis, followed by Wilcoxon signed-rank test for paired data to identify differences between values of the left and right body side. As data were not normally distributed, trunk angles and movement type (FW, BW; stance and swing phases), DistMBPH, as well as MaxH were compared between FW and BW using paired Wilcoxon signed-rank tests. Separate analyses were performed to compare FW, BW and SLL using Friedman tests. The level of significance was set at $P < 0.05$. To account for type I errors in the context of multiple comparisons, a false discovery rate (FDR) controlling procedure was applied to all analyses accepting a FDR of 15 % (Benjamini and Hochberg, 1995), identifying all P-values that were both below 0.05 as well as below their respective Benjamini-Hochberg critical value as significant.

Results

From nine horses, 27 measurement trials each of FW and BW were analysed. The number of forelimb stance phases (FSt), forelimb swing phases (FSw), hindlimb stance phases (HSt), and hindlimb swing phases (HSw) evaluated per horse are presented in Supplementary Table S1. In BW, four horses displayed solely synchronous diagonal limb pair movements, one horse showed disintegrated, asynchronous stepping throughout, and four horses varied between diagonal and non-diagonal stepping patterns. Nine forelimb SLLs (F-SLL) of five horses, and nine hindlimb SLLs (H-SLL) of six horses were correctly executed and thus used for analysis.

Table 1

Back angles in the sagittal plane measured dorsal between the middle of the withers, 16th thoracic, and 2nd sacral vertebra (D-angWmT16S2) and ventral between 16th thoracic, 2nd, and 4th sacral vertebra (V-angT16S2S4) during three forward walk (FW) and backward walk (BW) measurements of nine horses. Angles over the whole movement with up to three motion cycles are considered. Minimum, maximum and median given as median (minimum-maximum) are compared between FW and BW. Identical superscript letters indicate significant differences between FW and BW.

Angle	D-angWmT16S2 [°]		V-angT16S2S4 [°]	
Movement	FW	BW	FW	BW
Minimum	162.1 (153.7 – 165.2)	161.8 (155.6 – 167.6)	154.5^{c} (151.4 – 161.5)	154.1^{c} (144.2 – 160.9)
Median	164.8^{a} (160.5 – 166.9)	165.8^{a} (161.9 – 173.3)	157.3^{d} (154.2 – 164.0)	156.0^{d} (149.3 – 162.6)
Maximum	167.7^{b} (164.6 – 168.8)	169.8^{b} (164.8 – 179.5)	159.9^{e} (157.0 – 167.0)	157.8^{e}(152.5 – 165.8)

FW, Forward walk; BW, Backward walk; Wm, Mid-withers; T16, 16th thoracic vertebra; S2, 2nd sacral vertebra; S4, 4th sacral vertebra.

D-angWmT16S2, dorsal angle in the sagittal plane between markers Wm, T16, S2.

V-angT16S2S4, ventral angle in the sagittal plane between markers T16, S2, S4.

a: $P = 0.011$; b,e: $P = 0.021$; c: $P = 0.024$; d: $P = 0.012$; determined by paired Wilcoxon signed-rank test.

Comparison of parameters of the left and right

Medians of L-angWmT16S2 and L-angT16S2S4 were significantly different between left and right FSt, FSw, HSt, and HSw in either FW or BW, or both, i.e., in 10/16 comparisons. Medians of D-angWmT16S2 showed significant differences between left and right FSt and HSt of FW, i.e., in 2/16 comparisons. Based on these findings, lateral trunk angles for stance and swing phases of left and right limbs are reported separately, while the results of D-angWmT16S2 and V-angT16S2S4 are reported together for left and right FSt, FSw, HSt, HSw. Only median of the lateral position of left and right hindlimbs in FW swing phase were significantly different ($P = 0.021$), therefore left and right limbs were reported together for DistMBPH results.

Trunk angles in FW and BW

All ROM values are presented as (median; range) in the text, the underlying maximum and minimum angles of individual horses are listed in the respective tables. During BW, range of D-angWmT16S2 was significantly larger (7.0°; 12.6°) than in FW (5.6°; 7.4°) ($P = 0.017$), whereas V-angT16S2S4 ROM was similar in BW (4.9°; 5.9°) and FW (5.9°; 3.0°) ($P = 0.374$) throughout the movement (Table 1). In eight out of nine horses the median of D-angWmT16S2 and in all nine horses the median of V-angT16S2S4 showed more flexion of the back during BW than during FW. There were no significant differences between FW and BW for L-angWmT16S2 and L-angT16S2S4 throughout the movement (Supplementary Table S2). During stance phases of fore-and hindlimbs, ROM of L-angWmT16S2 and ROM of L-angT16S2S4 were larger than during swing phases, in FW and BW. In left and right HSw, L-angWmT16S2 ROM was significantly smaller during BW (left: 3.9°; 3.7°; right: 3.5°; 6.6°) than during FW (left: 5.4°; 6.0°; right: 6.2°; 6.4°) (left: $P = 0.028$; right: $P = 0.021$) (Supplementary Table S3a and S3b). Of V-

Table 2a

Back angles in the sagittal plane measured dorsal between the middle of the withers, 16th thoracic, and 2nd sacral vertebra (D-angWmT16S2) and ventral between 16th thoracic, 2nd, and 4th sacral vertebra (V-angT16S2S4); stance phases of fore- and hindlimbs in forward walk (FW) and backward walk (BW) of nine horses are considered, based on three measurements per horse and movement direction with up to four stance phases of fore- or hindlimbs per trial. Minimum, maximum and median given as median (minimum-maximum) are compared between FW and BW. Identical superscript letters indicate significant differences between FW and BW. Lower-case letters: $P < 0.05$; upper-case letters: $P < 0.01$.

Angle	D-angWmT16S2 [°]				V-angT16S2S4 [°]			
Movement	FW	BW	FW	BW	FW	BW	FW	BW
Stance phase	Forelimbs		Hindlimbs		Forelimbs		Hindlimbs	
Minimum	163.0^{A}	163.6^{A}	163.2^{c}	163.7^{c}	154.6^{e}	155.0^{e}	155.2^{g}	155.2^{g}
	(155.9 – 165.4)	(157.3 – 172.1)	(154.4 – 165.3)	(157.3 – 172.0)	(152.2 – 162.1)	(146.8 – 161.7)	(152.2 – 162.1)	(146.3 – 161.3)
Median	164.8^{b}	166.2^{b}	164.8^{d}	165.2^{d}	157.5	157.3	157.9^{H}	156.5^{H}
	(160.1 – 167.3)	(161.6 – 173.8)	(159.9 – 166.5)	(161.1 – 173.9)	(153.8 – 164.9)	(149.4 – 162.6)	(154.2 – 163.9)	(149.3 – 162.4)
Maximum	167.8	167.2	167.6	167.5	159.4^{f}	157.4^{f}	159.8^{i}	157.6^{i}
	(163.9 – 168.8)	(163.9 – 177.3)	(163.5 – 170.3)	(163.6 – 177.6)	(156.1 – 169.5)	(151.2 – 164.2)	(156.3 – 168.8)	(151.2 – 163.6)

FW, Forward walk; BW, Backward walk; Wm, Mid-withers; T16, 16th thoracic vertebra; S2, 2nd sacral vertebra; S4, 4th sacral vertebra.
D-angWmT16S2, dorsal angle in the sagittal plane between markers Wm, T16, S2.
V-angT16S2S4, ventral angle in the sagittal plane between markers T16, S2, S4.
A,H: $P = 0.008$; b: $P = 0.011$; c,f: $P = 0.021$; d,i: $P = 0.015$; e: $P = 0.036$; g: $P = 0.038$; determined by paired Wilcoxon signed-rank test.

Table 2b

Back angles in the sagittal plane measured dorsal between the middle of the withers, 16th thoracic, and 2nd sacral vertebra (D-angWmT16S2) and ventral between 16th thoracic, 2nd, and 4th sacral vertebra (V-angT16S2S4) compared during swing phases of forward walk (FW) and backward walk (BW), of nine horses, based on three measurements per horse and movement direction with up to six swing phases of fore- or hindlimb per trial. Minimum, maximum and median given as median (minimum-maximum) are compared between FW and BW. Identical superscript letters indicate significant differences between FW and BW. Lower-case letters: $P < 0.05$; upper-case letters: $P < 0.01$.

Angle	D-angWmT16S2 [°]				V-angT16S2S4 [°]			
Movement	FW	BW	FW	BW	FW	BW	FW	BW
Swing phase	Forelimbs		Hindlimbs		Forelimbs		Hindlimbs	
Minimum	163.3^{a}	164.8^{a}	163.1^{D}	163.8^{D}	157.2^{F}	155.3^{F}	155.2	155.2
	(157.0 – 165.8)	(158.1 – 171.6)	(157.3 – 165.7)	(158.2 – 172.0)	(152.7 – 163.3)	(147.1 – 161.9)	(152.6 – 162.2)	(147.5 – 162.0)
Median	164.1^{b}	165.7^{b}	164.3^{e}	164.9^{e}	158.4^{G}	155.9^{G}	157.7^{i}	156.0^{i}
	(159.9 – 166.6)	(162.0 – 173.0)	(159.9 – 166.7)	(162.4 – 173.0)	(153.9 – 164.8)	(148.7 – 162.7)	(154.2 – 164.0)	(148.6 – 162.8)
Maximum	166.1^{c}	166.6^{c}	166.8	167.0	159.0^{H}	156.7^{H}	158.8^{j}	156.7^{j}
	(163.1 – 167.7)	(163.3 – 175.4)	(163.5 – 168.8)	(163.6 – 174.9)	(155.4 – 167.2)	(150.0 – 163.2)	(155.5 – 168.4)	(149.4 – 163.5)

FW, Forward walk; BW, Backward walk; Wm, Mid-withers; T16, 16th thoracic vertebra; S2, 2nd sacral vertebra; S4, 4th sacral vertebra.
D-angWmT16S2, dorsal angle in the sagittal plane between markers Wm, T16, S2.
V-angT16S2S4, ventral angle in the sagittal plane between markers T16, S2, S4.
a,e: $P = 0.011$; b,j: $P = 0.015$; c,i: $P = 0.021$; D,F,G,H: $P = 0.008$; determined by paired Wilcoxon signed-rank test.

angT16S2S4, ROM was notably larger during HSt (5.4°; 4.3°) and HSw (3.6°; 3.4°) of FW compared to HSt (3.1°; 3.3°) ($P = 0.028$) and HSw (2.1°; 1.8°) ($P = 0.011$) of BW (Tables 2a 2b).

Comparing trunk angles in SLLs to FW and BW (with the smaller sample size)

The ROM of L-angT16S2S4 during F-SLL (1.3°; 1.3°) was significantly smaller than during FSw in BW (2.8°; 3.4°) ($P = 0.034$). The ROM of L-angWmT16S2 during H-SLL (2.7°; 2.1°) was less than during HSw in FW (5.7°; 5.6°) ($P = 0.004$) (Supplementary Table S4). Representing dorsoventral movement, D-angWmT16S2 was altered by 2.1° (1.2°) in H-SLL compared to 3.7° (1.3°) in HSw of FW ($P = 0.002$) (Table 3).

Hoof position and movement

In eight out of nine horses the median position of the hooves during the stance phase of FW was closer to the sagittal body axis both in fore- and hindlimbs than during BW (Fig. 2). Ranges of DistMBPH were greater in BW than in FW, during FSt ($P = 0.051$) and HSt ($P = 0.028$), whereas during FSw and HSw, ranges in BW were smaller than in FW, without statistically significant differences (Table 4). Compared to F-SLL (13.96 %hw), range of DistMBPH was significantly smaller in BW FSw (5.66 %hw) ($P = 0.034$) (Table 5). During stance phases of fore- and hindlimbs, minimum DistMBPH was detected around mid-stance, and maximum DistMBPH was reached at the end of stance, but the time of maximum and minimum DistMBPH in swing phases of BW and FW was highly variable. Results of MaxH comparing BW and FW of all nine horses (Table 6) and comparing SLLs to BW and FW are reported (Table 7).

Discussion

In the present study, the occurrence of Type I error cannot be fully excluded for all comparisons, and the conclusions reached should undergo additional validation in future studies. Based on the large number of comparisons this study includes (n=202), the risk of identifying random effects as significant was reduced choosing the Benjamini-Hochberg procedure, as it is widely applied in studies involving thousands of comparisons (Glickman et al., 2014). For the present study, the accepted rate of false discoveries was chosen based on the exploratory nature of the study, with additional experiments in future studies possible without incurring huge costs or risks. This method is not yet commonly used in equine biomechanic studies. However, reasonably similar human biomechanics studies used this procedure investigating knee biomechanics on ramp walking in patients with and without knee arthroplasty and a minimum of 144 comparisons using an accepted FDR of 10 % (Zhang et al., 2024), investigating effects of hamstring lengthening in humans with cerebral palsy comparing male and female patients accepting a rate of 20 % with more than 50 parameters investigated in a total of 218 limbs (White et al., 2019), and investigating walking mechanics after ACL reconstruction and MRI findings accepting a FDR of 15 % for a total of 192 comparisons (Williams et al., 2018). Following on from the above, a FDR of 15 % was deemed

Table 3
Back angles in the sagittal plane measured dorsal between the middle of the withers, 16th thoracic, and 2nd sacral vertebra (D-angWmT16S2) and ventral between 16th thoracic, 2nd, and 4th sacral vertebra (V-angT16S2S4) compared during swing phases of forward walk (FW), backward walk (BW), and single limb lifts (SLL) of five individual horses for forelimbs and of six individual horses for hindlimbs. Minimum, maximum and median given as median (minimum-maximum) are compared between FW, BW and SLL. Identical superscript letters indicate significant differences between FW and BW, or between FW and SLL.

Angle	D-angWmT16S2 [°]			V-angT16S2S4 [°]		
Movement	FW	BW	SLL	FW	BW	SLL
Forelimb swing phase						
Minimum	163.9 (160.8 – 165.8)	164.8 (162.2 – 171.6)	163.6 (162.2 – 168.1)	154.1^{a} (152.7 – 157.4)	151.8^{a} (147.1 – 155.3)	153.5 (149.8 – 155.2)
Median	165.5 (161.9 – 166.6)	166.3 (163.6 – 173.0)	164.7 (163.2 – 168.6)	155.8^{b} (153.9 – 158.4)	153.3^{b} (148.7 – 155.9)	153.9 (151.4 – 155.9)
Maximum	167.0 (163.1 – 167.7)	167.0 (165.3 – 175.4)	165.5 (163.8 – 169.8)	156.7^{c} (155.4 – 159.0)	155.2 (150.0 – 156.7)	154.4^{c} (152.3 – 156.4)
Hindlimb swing phase						
Minimum	163.2 (160.2 – 165.7)	163.5 (161.0 – 172.0)	164.2 (162.6 – 168.8)	154.0 (152.6 – 159.0)	153.1 (147.5 – 158.2)	153.7 (150.0 – 159.2)
Median	164.3 (161.4 – 166.7)	164.6 (162.4 – 173.0)	165.4 (163.3 – 169.9)	156.4 (154.2 – 163.4)	154.9 (148.6 – 159.4)	155.3 (151.8 – 160.8)
Maximum	166.7 (164.2 – 168.4)	166.0 (163.6 – 174.9)	166.1 (164.8 – 170.9)	157.6 (155.5 – 165.0)	156.0 (149.4 – 160.4)	156.3 (152.2 – 161.5)

FW, Forward walk; BW, Backward walk; SLL, Single limb lift; Wm, Mid-withers; T16, 16th thoracic vertebra; S2, 2nd sacral vertebra; S4, 4th sacral vertebra.
D-angWmT16S2, dorsal angle in the sagittal plane between markers Wm, T16, S2.
V-angT16S2S4, ventral angle in the sagittal plane between markers T16, S2, S4.
a,b,c: $P = 0.034$; determined by Friedman test.

acceptable for the present study.

The hypothesis that trunk ROM is smaller throughout BW compared to FW is rejected for D-angWmT16S2 and neither rejected nor supported for the other angles. In BW, the backwards shift of body mass during stance and protraction of limbs (Denoix, 2014) and the generation of force prior to swing and retraction of limbs demands stabilisation of the pelvis as it is leading in the direction of locomotion. This may imitate the effect of head and neck as balancing mechanism during FW (Moore, 2010; Zsoldos and Licka, 2015). In equines and humans, whole-body spatial stabilisation during locomotion is achieved by synergistic oscillations of head, neck, and trunk segments. The human trunk segment is primarily responsible for regulating and attenuating gait-related oscillations between the lower trunk and head (Kavanagh et al., 2006), whereas in horses, the neck also acts as a stabiliser due to its large size and mass, by minimising its own rotations and those of the head and trunk achieving stabilisation of all three (Dunbar et al., 2008). Elastic components connecting equine neck and trunk provide proprioceptive information regarding the relative position of body segments and store energy (Zsoldos and Licka, 2015). Increasing equine body stability during BW may be due to insecurity as it is less well trained than FW (Parelli et al., 1993) and visual appreciation in the direction of area of hind limb placement is marginal or non-existent (Murphy et al., 2009). Uncertainty requires enhanced body control during locomotion, this was shown in blindfolding with decreased postural stability during stance and a marginally larger base of support (Clayton and Nauwelaerts, 2014). During blindfolded FW, the maximum vertical displacement of the limb varied more, indicating a feed-forward effect of visual input on the gait of horses (Olsen et al., 2018).

Continuous lumbosacral flexion during BW, reflected in the results as low V-angT16S2S4 with a small ROM, will shift body mass onto the stable forelimbs to allow the hindlimbs to step backwards. A significantly larger maximum and a greater ROM was reached by D-angWmT16S2 in BW compared to FW, indicating a lifting of the back, an effect necessary to facilitate strengthening of the horse's core and therefore often desired in equine physiotherapy and in equestrian sports (Clayton, 2016; Shakeshaft and Tabor, 2020); the trunk muscle activation patterns creating this effect are yet to be studied. The results of the present study show that BW is useful to increase movement of the back

Table 5
Comparison of the distance between median body plane and forelimbs of five horses and between median body plane and hindlimbs of six horses during swing phases of forward walk (FW), backward walk (BW), and single limb lifts (SLL); up to three measurements per movement type with up to three swing phases per limb and trial are considered, expressed as percentages of the height at the withers (%hw). Minimum, maximum and median of the distance between median body plane and the respective hoof given as median (minimum-maximum) are compared between FW, BW, and SLL. Identical superscript letters indicate significant differences between FW and BW or between BW and SLL.

Phase	Forelimb swing			Hindlimb swing		
Movement type	FW	BW	SLL	FW	BW	SLL
Minimum [%hw]	10.55 (7.58 – 13.49)	15.18 (9.89 – 16.38)	9.37 (4.65 – 20.60)	9.46^{a} (5.96 – 9.91)	13.89^{a} (8.98 – 14.90)	9.53 (0.05 – 13.99)
Median [% hw]	13.55 (9.97 – 17.35)	16.83 (13.23 – 17.87)	18.11 (6.71 – 29.18)	12.36^{b} (10.04 – 13.16)	16.96^{b,c} (13.76 – 18.04)	12.66^{c} (2.95 – 15.15)
Maximum [%hw]	17.85 (14.35 – 19.36)	19.11 (16.92 – 21.21)	22.23 (14.80 – 40.14)	15.97 (15.00 – 17.94)	19.01 (16.77 – 20.91)	16.77 (14.93 – 28.23)

FW, Forward walk; BW, Backward walk; SLL, Single limb lift; %hw, Percentage of the height at the withers.
a: $P = 0.012$; b: $P = 0.028$; c: $P = 0.028$; determined by Friedman test.

Table 4
Distance between median body plane and hooves during stance and swing phases of forward walk (FW) and backward walk (BW) of nine horses, based on three measurements per horse and movement direction with up to three swing or stance phases per limb and trial, expressed as percentages of the height at the withers (%hw). Minimum, maximum and median of the distance between median body plane and the respective hoof given as median (minimum-maximum) are compared between FW and BW. Identical superscript letters indicate significant differences between FW and BW. Lower-case letters: $P < 0.05$; upper-case letters: $P < 0.01$.

Phase	Forelimb stance		Hindlimb stance		Forelimb swing		Hindlimb swing	
Movement type	FW	BW	FW	BW	FW	BW	FW	BW
Minimum [%hw]	7.47 (5.64 – 9.18)	7.76 (5.78 – 13.21)	8.01^{c} (6.10 – 10.02)	9.71^{c} (7.76 – 12.93)	9.52^{f} (7.58 – 13.49)	12.76^{f} (9.89 – 16.38)	9.45^{i} (5.96 – 10.98)	11.89^{i} (8.56 – 14.90)
Median [%hw]	10.76^{a} (8.16 – 11.83)	11.26^{a} (8.37 – 14.70)	10.18^{d} (8.67 – 11.21)	12.61^{d} (10.04 – 14.69)	13.55^{g} (9.97 – 17.35)	15.92^{g} (12.97 – 17.87)	12.21^{J} (10.04 – 13.42)	15.33^{J} (12.98 – 18.04)
Maximum [%hw]	14.39^{b} (13.52 – 15.88)	18.29^{b} (13.18 – 21.55)	12.99^{e} (11.37 – 15.70)	16.99^{e} (14.53 – 19.65)	17.39^{h} (14.35 – 19.36)	19.11^{h} (16.92 – 21.21)	15.89^{k} (12.53 – 17.94)	18.53^{k} (16.19 – 20.91)

FW, Forward walk; BW, Backward walk; %hw, Percentage of the height at the withers.
a: $P = 0.038$; b,e,f,h,i,k: $P = 0.011$; c: $P = 0.050$; d: $P = 0.015$; g: $P = 0.028$; J: $P = 0.008$; determined by paired Wilcoxon signed-rank test.

Table 6

Summary statistics comparing maximum hoof height and its occurrence during forelimb swing phases and hindlimb swing phases of forward walk (FW) and backward walk (BW) of nine horses, based on three measurements per movement direction with up to three swing phases per limb and trial. Identical superscript letter indicates significant difference between FW and BW.

	Maximum height [%hw]				Occurrence of max. height [%dsw]			
Limb	Forelimbs		Hindlimbs		Forelimbs		Hindlimbs	
Movement	FW	BW	FW	BW	FW[A]	BW[A]	FW	BW
Minimum	2.66	3.01	2.27	1.73	31.4	48.9	38.3	47.2
Median	4.26	4.39	3.75	4.49	42.8	58.6	54.6	51.1
Maximum	5.88	6.16	5.57	9.04	52.3	65.8	80.4	64.2

FW, Forward walk; BW, Backward walk; %hw, Percentage of the height at the withers; %dsw, Percentage of the duration of the swing phase at which maximum height was reached.

A: $P = 0.008$; determined by paired Wilcoxon signed-rank test.

not dissimilar to water treading on a treadmill with the water level at the tarsus or higher, however due to different methodologies results are not fully comparable (Nankervis et al., 2016). Walking in stifle-high water additionally causes significant 3.0° extension around the 13th thoracic vertebra compared to walking on the dry treadmill, possibly due to the higher head and neck position (Nankervis et al., 2016), an effect not observed at T16 during BW.

The ROM results of L-angWmT16S2 and D-angWmT16S2 during overground FW agree with a previous treadmill study (Licka et al., 2001). In the present study, differences between left and right limbs were found for L-angWmT16S2 and L-angT16S2S4 in the majority of comparisons. Laterality has been described as idiosyncratic in horses (Murphy et al., 2005), but in the present study additional factors may have created the significant body side differences found, i.e. their preceding experiences with handling and training which traditionally favours leading horses from their left side (Byström et al., 2020). The difference in gait patterns of FW and BW is also relevant. In BW, horses commonly use a symmetrical diagonal step pattern as in trot but without a suspension phase (Denoix, 2014); a disintegrated, four-beat rhythm is displayed less often. This was also observed in the present study, where backwards locomotion was mostly diagonal. However, the variable BW pattern led us into looking at trunk movement during swing and stance phases of each limb.

Flexion in the lumbosacral region was more stable during SLLs than during swing phases of FW but less than in swing phases of BW. In contrast to SLLs, where limb movement was mainly vertical, FW and BW comprise horizontal and vertical limb movement components (Deliagina et al., 2019). Laterolateral trunk movement was less in SLLs than during locomotion, implying that three limbs at stance are sufficient to stabilise the trunk. Different to horses, human SLL is a considerable challenge to body stability with the ankle as the primary stabiliser on firm ground and more proximal body parts having an increased role under more challenging conditions, such as uneven surfaces (Riemann et al., 2003) or lack of visual information (Wang et al., 2014).

One feature of body stability is the area of support, and in BW the wider support base creates additional stability. In FW and BW, considerable symmetry of left and right limb movements was found, as in hindlimbs of healthy horses during BW (Seino et al., 2019). With the hoof on the ground, the trunk moves laterally over the limb reaching minimum DistMBPH around mid-stance with DistMBPH greatest at the end of stance phase. A highly variable DistMBPH pattern was observed during limb swing possibly attributed to plaiting or winging as displayed commonly by horses with non-physiological limb or toe conformation (Shahkhosravi et al., 2021). In Seino et al. (2019), hindlimbs of healthy horses reached a mean abduction angle of 22.7° during SLL, slightly more than abduction angles at MaxH during H-SLL calculated to be 12.9° in the present study, maybe because hindlimbs were lifted less and sometimes even adducted during SLL. In our study population without clinically detectable neurological deficits, and in the healthy controls in a study on shivering, hindlimbs were lifted to similar heights during BW, with large variations between individuals, and FW, in contrast to increased hoof elevation described in horses suffering from shivering (Draper et al., 2015; Seino et al., 2019). Almost all horses of the present study reached the greatest MaxH during SLLs, similar to the lifting of hindlimbs of the healthy controls in Seino et al. (2019). As expected, neither hyperflexion nor obvious abduction of hindlimbs during BW were observed in the horses in the present study. Forelimb MaxH occurred significantly later in BW than in FW, at a median of 59.6 %dsw and 44.8 %dsw respectively, raising the question whether swing phase characteristics of forelimbs in BW mirror those in FW, so that forelimb movement in BW is following the same flight path in the opposite direction than in FW and not a simple inversion of FW. During FW, the %dsw of MaxH in hindlimbs was very variable, therefore making a comparison to BW difficult.

The camera setup available for the present study with its limited measurement volume allowed for measurement of up to three motion cycles in FW and BW, which is a potential limitation, as healthy horses in Seino et al. (2019) backed for ten strides without hesitation. The use of a treadmill for standardization of speed was no option for the measurement of BW for safety reasons. Although kinematics of similar or even smaller numbers of horses have resulted in very relevant scientific findings, a larger number of horses would have increased statistical power. The influence of different breeds and sizes of horses included in the present study was only partially offset by normalizing distances to the height at the withers, and results can claim to be relevant only for some types of horses.

Conclusions

Compared to forward walking, backing horses lift their backs with marked lumbosacral flexion with wide limb placement. This creates a larger area of support for this less frequently used locomotion, where awareness of obstacles in the direction of movement and lack of head and neck for stabilisation create some insecurity for the horse. During lifting of single limbs, the trunk is very stable, making it a valuable

Table 7

Summary statistics comparing maximum hoof height and its occurrence during forelimb swing phases of five horses and during hindlimb swing phases of six horses in forward walk (FW), backward walk (BW), and single limb lifts (SLL), based on up to three measurements per horse and movement type with up to three swing phases per limb and trial. Identical superscript letters indicate significant differences between FW and BW or between FW and SLL.

	Maximum height [%hw]						Occurrence of max. height [%dsw]					
Limb	Forelimbs			Hindlimbs			Forelimbs			Hindlimbs		
Movement	FW	BW	SLL	FW[a]	BW	SLL[a]	FW[b]	BW[b]	SLL	FW[c]	BW	SLL[c]
Minimum	2.66	3.01	3.58	2.27	1.73	2.48	39.9	50.8	31.7	38.3	47.2	25.7
Median	4.38	4.39	6.45	3.63	4.51	9.20	44.8	59.6	51.3	57.5	49.7	39.9
Maximum	5.88	6.16	23.87	5.57	6.66	16.09	49.0	65.8	53.0	80.4	58.3	63.2

FW, Forward walk; BW, Backward walk; SLL, Single limb lift; %hw, Percentage of the height at the withers; %dsw, Percentage of the duration of the swing phase at which maximum height was reached.

a: $P = 0.012$; b: $P = 0.034$; c: $P = 0.028$; determined by Friedman test.

exercise for the trunk as well as for (all) the limbs.

CRediT authorship contribution statement

I.D. Jobst: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **R.R. Zsoldos:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **T.F. Licka:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

None of the authors has any financial or personal relationships that could inappropriately influence or bias the content of the paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.tvjl.2024.106202.

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