The difference in kinematics of horses walking, trotting and cantering on a flat and banked 10m circle

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(Flat versus banked circle locomotion)

Symbols & abbreviations

(3-D) Three dimensional

(COM) Centre of mass

(DIPJ) Distal interphalangeal joint

(LCS) Laboratory coordinate system

(MPJ) Metacarpophalangeal joint

(McIII) Metacarpus

(MtIII) Metatarsus

(PIPJ) Proximal interphalangeal joint

(P1) Proximal phalanges

(SCS) Segment coordinate system

Key words

circle; locomotion; centripetal force; kinematics; limb inclination; curve

Summary

Background: Locomotion adaptation mechanisms have been observed in horses, but little information is available in relation to banked and non-banked curve locomotion, which might be important for correct training.

Aim: To determine if adaptation mechanisms in horses existed when moving on a banked compared to a flat curve and whether adaptation was similar in different gaits.

Materials and Methods: Eight infra red cameras were positioned on the outside of a 10 m lunging circle and calibrated. Retroreflective markers were used to define left and right metacarpus (McIII) and proximal phalanges (P1), metatarsus (MtIII), head and sacrum. Data were recorded at 308 Hz from six horses lunged at walk, trot and canter on a flat and 10 degree banked circle in a cross over design. Measurements extracted were speed, stride length, McIII inclination, MtIII inclination, relative body inclination and duty factor. Data were smoothed with a 4th order Butterworth filter with 30 Hz cut-off. ANOVA was used to determine differences between conditions and limbs.

Results: Adaptation mechanisms were influenced by gait. At canter inside forelimb duty factor was significantly longer ($P<.05$) on a flat curve compared to a banked curve, at walk this was reversed. McIII inclination, MtIII inclination and relative body inclination were significantly greater ($P<.05$) at trot and canter on a flat curve, so more inward tilt was found relative to the bearing surface.

Conclusion: Adaptation to curved motion is gait specific. At faster gaits it appears that horses negotiate a banked curve with limb posture closer to body posture and probably with demands on the musculoskeletal system more similar to straight canter.

Introduction

The kinematics of walk, trot and canter gaits have been studied over ground and using treadmills in two dimensions (Barrey *et al*., 1993; van Weeren *et al*., 1993; Buchner *et al*., 1994; Clayton, 1994; Back *et al*., 1996; Galisteo *et al*., 1998; Galisteo *et al*., 2001; Clayton *et al*., 2002) and three dimensions (Chateau *et al*., 2004; Chateau *et al*., 2006; Hobbs *et al*., 2006; Clayton *et al*., 2007a; 2007b; Gomez Alvarez *et al*., 2009). From these studies adaptation mechanisms have been observed during treadmill locomotion (Barrey *et al*., 1993; Buchner *et al*., 1994; Gomez Alvarez *et al*., 2009) and other studies have reported adaptations due to shoeing regimens and hoof conformation, which include Clayton *et al*. (1990), Roepstorff *et al*. (1999) and van Heel *et al*. (2006). To date, few studies have investigated adaptations in kinematics during locomotion on a curve.

Curve negotiation involves producing an inwardly directed ground reaction force (GRF) during the stance phase which results in centripetal acceleration (see Fig. 1) and this presents different challenges for different vertebrates. Greyhounds are not constrained when running on a curve as their body weight is supported mainly by their forelimbs and locomotion is powered by torque about the hip joint and by back extension (Usherwood and Wilson, 2005). In contrast, the muscles that power sprinting in humans are loaded by weight induced compression forces along the leg and a greater proportion of the maximum muscular effort must be directed medio-laterally in order to develop centripetal acceleration (Usherwood and Wilson, 2005). Chang and Kram (2007) found the inside leg to be particularly ineffective at generating push off forces for propulsion in humans and proposed that this is due to a need to optimise the alignment of the resultant GRF vector with the long axis of the leg. They suggested that muscles required to stabilize joints in the frontal plane, which have a negligible effect in straight path sprinting, are required in curve sprinting to realign and stabilize the long axis of the leg. This increased muscle activity may therefore be inhibiting leg extension force during curve running and as vertical GRF decreased more than could be explained by a re-distribution of force to the medio-lateral direction. Usherwood and Wilson (2006) also suggested that tighter radii result in greater increases in duty factor, which Chang and Kram (2007) again found to be greater for the inside leg.

Adaptations to curve motion in horses have been reported in two recent studies. Clayton and Sha (2006) investigated head and body centre of mass (COM) movement trotting on a flat surface with a circular path of radius 2.83 ± 0.62 m. They found an average tilt of the COM towards the inside of the circle of 14.8 ± 2.8 degrees and medio-lateral oscillation of the COM outwards with outside forelimb stance and inwards with inside forelimb stance. In addition, the inclination of the COM in the frontal plane was more vertically oriented around the time of ground contact with the inside forelimb. Chateau *et al*. (2005) investigated adaptations of the inside, distal forelimb during a tight turn at walk. It was reported that the limb adducted through the stance phase substantially more until heel off to cover the ground in the direction of movement. The distal interphalangeal joint (DIPJ) underwent substantial internal (medial) rotation during the weight bearing phase of the turn, the proximal interphalangeal joint (PIPJ) rotated internally and the metacarpophalangeal joint (MPJ) also rotated internally in the second half of the stance phase as the joint flexed. As body mass was brought over the limb in the direction of the turn the limb adducted, there was a large external rotation of the hoof to lift off and the medial side of the hoof left the ground first. This rotation was associated with sudden external rotation of the PIPJ and DIPJ which realigned the distal segments that were internally rotated at the end of the weight bearing phase. From these studies it is clear that adaptations to curve motion are also found in horses, but constraints placed on the limbs at faster speeds are unknown.

Fredricson and Drevemo (1971) recognised that the characteristics of the surface, banking, curve and gradient as well as surface variation will affect the trotting action. In this respect they suggested that at high speed good horses can compensate for many of these factors, but to the expense of wear and tear on their limbs. The risk of injury to the distal joints when negotiating curves may increase further for horses performing at faster gaits and over longer time periods, as Johnston *et al*. (1999) found stride length, stance time and joint excursion during stance to increase with fatigue. Hill (2003) remarked that most catastrophic injuries in racing will occur in turns and in the stretch run to the finish. In a study of 58 horses suffering serious accidents during racing, Ueda *et al*. (1993) also came to the conclusion that injuries were more likely to occur in turns. Despite this, studies of racing injury risks (Stephen *et al.*, 2003; Parkin 2008) have yet to address factors such as the design of the course, the radius of the curves on the course, and whether these curves are banked or not, which was also suggested by (Anthenill *et al.*, 2007). Evidence suggests that the greatest injury risks during turning are to the forelimbs, but there is conflicting information on the prevalence of injury to left and right limbs, considering that many racetracks are counter-clockwise. Peckham (2009) reported a prevalence of injuries to left forelimbs on the Polytrack at Kentucky during a holiday meet and in a study by Hill (2003) from a total of 27 third metacarpal bone (McIII) fractures, 19 were to the left fore. This was supported by Bertone (1997) who suggested that typical Standardbred condylar fractures are a left front lateral injury. However, right sided carpal injuries have previously been reported in the USA (Schneider *et al.*, 1988) and UK and Australian studies have found injuries to left and right forelimbs to be equally represented (Bathe, 1994; Verheyen and Wood, 2004; Boden *et al*., 2006).

In the distal limb at low loads the DIPJ accounts for most of the motions outside the sagittal plane, but with increasing load the involvement of this joint becomes less whereas the involvement of the PIPJ and MPJ increases (Chateau *et al*., 2002). Out of plane rotations will increase stress on the distal joints during weight bearing (Denoix, 1999) and as a result degenerative joint disease is most frequently found in horses that make tight turns or twisting movements (Stashak, 2002a; Swanson, 1988; McDiarmid, 1998). Lunging is often used in lameness assessment as most clinical orthopaedic conditions of the horse are known to be increased on the turn (Stashak 2002b), mostly for the inside limb, but in some defined conditions such as proximal suspensory desmitis the lameness may also be exacerbated in the outside limb (Dyson, 2007). Further investigation of the adaptation mechanisms of the horse on banked and unbanked curves could lead to more scientifically qualified exercise suggestions for horses recovering from orthopaedic injury.

The use of banking on curves of different sporting venues is widespread and well designed tracks are known to allow better curve negotiation (Schuermann, 2008), as a component of body weight assists in providing inwardly directed force at the ground (Hay, 1993) (see Fig. 1b). Despite this, little information is available on adaptation of horses to curved and banked curve locomotion which may be important for correct training. The aims of this study were therefore to determine whether there was an adaptation mechanism in horses during lunging on a banked curve compared to a flat curve and whether this adaptation mechanism was similar in different gaits. Based on previous studies of curve and banked curve motion (Greene 1985; 1987; Hay, 1993; Clayton and Sha, 2006; Usherwood and Wilson, 2005; Chang and Kram, 2007) it was hypothesised that forelimb inclination and relative body inclination will be greater on a flat surface compared to a banked surface, as a component of bodyweight assists in providing inwardly directed force at the ground on a banked surface. That there will be a need for relatively longer duty factors on a flat surface at trot and canter, as more resultant force will be required to maintain speed. That inclination and duty factor will be more pronounced in the inside forelimb.

Method

Animals

Ethical approval was obtained for this project from the UCLan and the University of Edinburgh animal projects committees. Six sound veterinary school horses (height at the withers 154 ± 8 cm and body mass 529 ± 25 kg (mean ± s.d.) were used in the study. Horses were lunged regularly at walk, trot and canter for 4 weeks prior to the commencement of the study to increase fitness levels and habituated to the test set up on the lunge at walk, trot and canter prior to testing in both flat and banked conditions.

Data Collection

Eight infra-red cameras[1] were positioned in an arc configuration on the outside of a 10 m lunging circle and calibrated to a horizontal-vertical laboratory coordinate system (LCS) using a spirit level. The lunging circle surface used for both conditions was prepared from wetted and then pressed sand and rubber particles. The average penetration depth of the surface with a Longchamps Pentrometer was 7.3 cm allowing plastic deformation to an average hoof depth of 4.8 ± 1.9 cm and 4.5 ± 1.8 cm on the flat and banked surfaces respectively. The measurement volume was 5 m long by 2 m wide by 2 m high, the maximum residual from the cameras was 0.42 mm and the wand measurement error was 1.35 mm for a 750.5 mm wand. A marker set of 30 retro-reflective markers were used to define the left and right McIII, proximal phalanges (PI), metatarsus (MtIII), head and sacrum. A three-dimensional (3-D) marker set was used for McIII and PI using both anatomical markers (markers that define the segment end points, joints and segment orientation) and tracking markers (markers that track the movement of that segment through 3-D space) as shown in Fig. 2a. A static trial was recorded with both anatomical markers and tracking markers in position whilst the horse stood square, from which the tracking markers are referenced to their anatomical position on the segment. Anatomical markers were positioned on the medial and lateral locations of the proximal head of McIII (positioned between McIII and medial and lateral splint bones) and the proximal site of attachment of the proximal collateral ligaments of the MPJ and PIPJ. Tracking markers were positioned on medial proximal, medial distal and the lateral mid-shaft of McIII and proximal medial, proximal lateral and the distal midline of PI. These locations were used to minimize soft tissue artefacts and also to ensure non co-linearity (a requirement for 3-D tracking). This method was based on the Calibrated Anatomical Systems Technique (Cappozzo *et al*. 1995; 2005). The anatomical markers were then removed.

Procedure

A cross over design was used such that 3 horses were lunged first on the flat and 3 horses were lunged first on the bank. Kinematic data from the tracking markers were recorded from the horses lunged on a 10 m circle at walk, trot and canter turning to the left and right at 308 Hz. The starting turn direction was randomised for each horse and for each condition. Forty seconds of data were collected for each trial to ensure that a sufficient number of strides could be extracted for each gait and each condition. The trials were digitised in Qualisys Track Manager[1], exported to three dimensional (3-D) motion analysis software[2], separated into and normalised to full strides. Foot strike and toe off were determined from inspection of the vertical velocity (Mickelborough *et al*. 2000) curves of left and right forelimb lateral PI and distal MtIII tracking markers. The kinematic data were filtered with a low pass 4th order Butterworth filter with a cut off frequency of 30 Hz from inspection of the canter data and as

20 Hz is commonly used for lower forelimb data at walk and trot (Chateau *et al*. 2006; Strobach *et al*. 2006). For each subject an ensemble average of a minimum of 3 stance phases for each leg, each condition and each turn direction was computed from replicate walks, trots and canters.

Calculations

The origin of the LCS was defined with X-axis as cranio-caudal (in the direction of motion), the Y-axis as medial-lateral (towards the inside-outside of the circle) and the Z-axis as vertical (see Fig. 2). From the LCS origin coordinates, the normal (perpendicular) to the bearing surface for flat and banked conditions was defined, which was vertical for the flat surface and at 10 degrees inwards from the vertical for the banked surface (see Fig. 1). All inclinations were measured from the normal for that surface (see Fig. 1 and 2). Speed was calculated from the resultant velocity of the X and Y sacrum marker velocity components in the LCS. Stride length was calculated from the resultant of displacement of the X and Y components of PI in the LCS from left foot strike to left foot strike and right foot strike to right foot strike. Duty factor was calculated as the ratio of stance time (foot strike to toe off) to stride time (foot strike to foot strike).

Segment position and orientation within the LCS was determined in two stages using a similar method to that described by Clayton and Sha (2006): 1) Position and orientation were defined relative to the origin of the LCS in Visual 3D[2], 2) Position and orientation were extracted at foot strike and the coordinate system was then rotated to their relative position on the curve in Excel[3] (see Fig. 3). Stage 1: For McIII and PI, a segment coordinate system (SCS) was defined with respect to the calibrated LCS (Cappozzo *et al*., 1995; Hobbs *et al*. 2006; Clayton *et al*. 2007b) and from this measurement the segment end point positions relative to the origin of the LCS were determined as described by Hobbs *et al*. (2006). For MtIII, segment position in the LCS was determined using proximal and distal tracking marker coordinates. Similarly, relative body inclination in the LCS was determined using the coordinates of the sacrum marker relative to the stance limb MtIII distal marker. Stage 2: For each foot strike the coordinates of each proximal and distal marker/segment end point were transposed to a new coordinate system that defined the X' axis at a tangent to the curve and Y' axis radially inwards. Coordinates of the proximal and distal end points/markers in Y'-Z plane were then used to calculate McIII, MtIII and relative body inclination (see Fig. 3).

Data analysis

Mean and standard deviations were calculated for speed, stride length, duty factor, McIII inclination, MtIII inclination and relative body inclination at walk, trot and canter. A Kolmogorov-Smirnov test was used to test for normality. For speed a 2 (flat vs. banked) by 2 (left turn vs. right turn) ANOVA was conducted. For the other dependent variables a 2 (flat vs. banked) by 2 (inside leg vs. outside leg) by 2 (left turn vs. right turn) ANOVA was conducted in SPSS[4]. This was done separately for each gait for the dependent variables stride length, duty factor, McIII, MtIII, and relative body inclination. In the instance turn direction did not influence the analysis this was removed from the model. In the instance of a significant interaction effect post-hoc comparisons were conducted using Fisher LSD[5]. Significance was set at $P < .05$.

Results

All data were normally distributed except for duty factor at walk on the flat and McIII inclination at walk. A log transformation was conducted for these data.

Speed

Results for speed at walk, trot and canter gaits on left and right turns is shown in Table 1. Turn direction did not influence speed and as such was removed from the model. A significant surface angle effect (flat vs. banked) was found for walk, (F(1,22) = 4.53; P = .05; η^2 = .17) with higher speeds on the flat (1.54 m s^{-1}) than the banked surface (1.40 m s^{-1}). No differences were found for trot (F(1,22) = 0.91; P = .35; η^2 = .04) or canter (F(1,22) = 0.01; P = .94; η^2 = .00).

Stride length

Mean and standard deviations for stride length, duty factor and McIII, MtIII and relative body inclination at walk trot and canter on flat and banked curves are shown in Table 2 whereas Table 3 shows the results of the analysis of variance. There was a significant leg main effect for walk and canter for stride length. A shorter stride length was found for the inside leg (1.66 m walk; 2.50 m canter) than the outside leg (1.77 m walk; 2.65 m canter). There were no effects for surface angle (flat vs. banked) or interaction effects. There was no effect for turn direction on stride length.

Duty factor

There was a significant main effect for surface angle at walk. Duty factor was higher for the banked surface (66.79%) than the flat (65.18%) surface. There was no interaction or leg main effect at walk. There was a significant interaction effect for trot and canter. Post-hoc comparisons for trot showed that duty factor for the flat inside leg (45.65%) was significantly longer than the flat outside leg (43.07%; P = .02) and the banked inside leg (42.92%; P = .02). For canter, post-hoc comparisons showed that the banked inside leg differed significantly from the flat inside leg (P = .001) and the flat outside leg (P = .04), but not from the banked outside leg (P = .06). There was no effect of turn direction for duty factor.

McIII inclination

There was no effect for turn direction for McIII inclination. For all three gaits McIII inclination, which reflects the magnitude of limb adduction, was found to be significantly larger for the flat in comparison to the banked condition (walk 0.1 vs. -10.2 degrees; trot 18.2 vs. 7.2 degrees; canter 25.7 vs. 17.7 degrees). Similarly, a leg main effect was found for all three gait patterns. McIII inclination was found to be larger for the inside leg for walk (1.9 vs. -12.0 degrees), trot (15.0 vs. 10.4 degrees) and canter (24.3 vs. 19.1 degrees) compared to the outside leg.

MtIII inclination

Again, there was no effect for turn direction for MtIII inclination. There was a significant main effect for surface angle for all three gaits. MtIII inclination was larger in walk (6.7 vs. -2.53 degrees), trot (19.3 vs. 10.1 degrees), and canter (26.6 vs. 20.8 degrees) gaits. Also, the inside leg had a larger MtIII inclination (24.1 degrees) than the outside leg (15.3 degrees) in the trot condition.

Relative body inclination

There was no effect for turn direction for relative body inclination. At walk (5.3 vs. -2.1 degrees), trot (18.8 vs. 9.5 degrees) and canter (24.8 vs. 18.2 degrees) relative body inclination was larger in the flat condition in comparison to the banked condition. In addition, at trot and canter relative body inclination was significantly greater for outside hind limb foot strike than for inside hind limb foot strike.

Discussion

This study aimed to determine whether horses adapt their locomotion on a banked curve compared to a flat curve and if so, whether these adaptation mechanisms were similar in different gaits. The results show that at faster gaits (trot and canter) an increase in duty factor for the inside forelimb compared to the outside forelimb is dependent on surface angle, so an increase could be expected on a flat, but not necessarily a banked surface. Duty factor was also significantly greater on a flat surface compared to a banked surface at canter and at both trot and canter the increase was significant for the inside forelimb, which in part supports our hypotheses. Greater forelimb (McIII) inclination and relative body inclination were found on a flat surface compared to a banked surface, supporting our a priori hypothesis. In addition, a similar pattern was observed for the hind limbs (MtIII inclination). So, more tilt relative to the ground was recorded on a flat surface in comparison to the banked surface. Inside forelimb (McIII) inclination compared to outside forelimb (McIII) inclination was also more pronounced on the flat surface in comparison to the banked surface, although care must be taken when interpreting these results as a larger angle would be expected in relation to the surface. These results were therefore considered with respect to relative body inclination to reflect how much each limb adducted.

To negotiate a curve the outside legs have to travel further than the inside legs, so a longer stride for the outside leg at all gaits was expected. The introduction of a banked curve did not change this difference between limbs, but at walk a shorter stride length for both limbs was found. This may be because a banked curve presents an unlevel surface that is more difficult to negotiate and this therefore slowed the horses down, reducing stride length.

At walk the increase in duty factor on a banked curve may also relate to the reduction in speed. In contrast, at canter on a flat curve, duty factor increased significantly for the inside leg. Although the horses were not negotiating the curves at maximum speed, the inside leg may be kept on the ground for longer on a flat curve to produce sufficient inwardly directed force at the ground to stay on the curve in addition to maintaining propulsive forces. Usherwood and Wilson (2005) suggested that in greyhounds this is a role of the forelimbs and in humans Chang and Kram (2007) found that larger medio-lateral forces were generated by the inside leg. On a banked curve, this requirement may have been reduced as a component of body weight assisted in providing inwardly directed force at the ground (Hay, 1993). The interaction effect found at trot and canter however may suggest that the difference in timing relates to the position of the limbs relative to the ground. On a flat curve the horse tilts more, so their outside leg is further away from the ground and consequently it may take longer for this limb to make contact with the ground, on a banked curve this situation is reversed. So, relative body position to the bearing surface in addition to the requirement to generate inwardly directed GRFs may influence duty factor for the forelimbs.

McIII inclination at foot strike occurs during straight locomotion as a result of global limb adduction (Chateau *et al*., 2004; Hobbs *et al*., 2006; Clayton *et al*., 2007a; 2007b). In contrast, during a tight turn Chateau *et al*. (2005) reported McIII abduction of the inside leg at foot strike with adduction increasing throughout stance. They suggested that adducting the limb during the turn positions the limb further under the body which allows the horse’s body mass to travel over it in the direction of motion. In this study where a larger curve was negotiated, similar magnitudes of inclination to McIII adduction previously reported for straight line walk at foot strike were found for both inside and outside forelimbs on a flat curve. On a banked curve however, it appears the body leans outwards as if traversing a slope and consequently to maintain balance the forelimbs are more inclined towards the outside of the circle, which is most pronounced in the outside forelimb. These inclinations may reflect the need to control the location of the COM under the influence of gravitational forces when the horse is moving slowly.

At faster gaits greater McIII inclination was found, which corresponds with greater body inclination, so the more the body tilts, the more the limbs tilt. Tilt was also more pronounced on a flat curve. These findings support the theory described in Fig. 1a and b. The implication of these findings are that additional frontal plane forces and moments expected when negotiating a curve together with a more adducted limb relative to the ground may increase out of plane stresses on the distal joints, particularly on a flat curve (Denoix, 1999; Chateau *et al*., 2002). Injuries reported from racing tend to include lateral condylar fractures, distal phalanx wing fractures, medial proximal sesamoid bone fractures and fractures of PI, which tend to be compression fractures (Bertone, 1997; Boden *et al*., 2006). The forelimbs may also be more susceptible to collateral ligament injuries and degenerative joint disease when frontal plane forces become unbalanced. For this variable, overload is more likely to relate to misalignment of the resultant GRF with the inside forelimb when the requirement for centripetal force development is large.

MtIII inclination was found to be similar for the outside hind limb compared to the inside hind limb at walk and also similar to the inclination of the body, so little adduction was expected. At trot and canter MtIII inclination followed the pattern of McIII and relative body inclination, tilting more as the body tilted. From inspection of relative body inclination it appears that greater limb adduction was found at trot and this was more pronounced on a banked curve. Bringing the hind limbs under the body is required to provide optimal forces for propulsion. It was surmised that where this did not occur the hind limbs may have been required to assist the forelimbs in balancing the body through the turn.

The body was inclined towards the inside of the circle at all gaits with the magnitude of inclination increasing with gait, except for the banked curve at walk where the horses balanced by tilting their bodies towards the outside of the circle. In this study relative body inclination at trot on a flat 10 m circle was slightly larger (approximately 4 degrees) than the average tilt of the COM at trot found by Clayton and Sha (2006) on a 6 m circle. Trotting speed was faster in this study (3.7 $m.s^{-1}$ compared to 2.3 $m.s^{-1}$ average speed used by Clayton and Sha (2006)). Although their radius was smaller, there is a squared effect of speed on the magnitude of centripetal force, so speed will influence tilt more than the radius of the curve. An increase in tilt with gait, particularly on a flat curve is expected to relate to the need to use body weight to assist in balancing increasing rotational moments (Hay, 1993). Medio-lateral oscillation of the COM was reported by Clayton and Sha (2006) and in this study there was also evidence of body oscillation at trot and canter, although this measurement is sensitive to differences in outside and inside hind limb placement. However, this finding may be important in terms of injury risk to the outside fore and hind limbs, as greater oscillation of the body could increase compressive forces on these limbs.

When lunging their horses, Clayton and Sha (2006) only turned to the left. The authors remarked that individual differences may be evident when turning clockwise versus anti-clockwise, due to asymmetries in strength, suppleness and neural programming. In this study, none of the variables were significantly influenced by turn direction, although some variability is evident. In addition, horses were prepared to take part in the study using a 4 week programme of lunging, designed to improve fitness. Their physical capability to negotiate turns however is likely to be different to other sports and performance horses that are trained to remain upright on a circle or trained to gallop at maximum speed around turns. A recent study by Murray *et al*. (2010) found dressage horses that were lunged on a regular basis to be at a reduced risk of lameness, which does suggest that demands may be discipline specific. Further work is needed to explore differences between horses competing in different disciplines.

Limited information is available on equine curved locomotion, despite the prevalence of circles, twists, turns and curves used in most equine disciplines. As technology advances we will undoubtedly be able to measure curved locomotion in more detail, but currently collecting detailed information presents many challenges. Soft tissue artefacts are present in these data as the study used non-invasive techniques, but errors are expected to be comparable between surface angles for each horse and each gait. The choice of marker set was based on the tracking capabilities of markers within the capture volume. Lunging was used to capture curved locomotion, consequently cameras could not be positioned on the inside of the circle. Cameras were therefore optimised to capture limb and body posture from the outside of a circle, but this did limit their tracking capabilities in relation to the trunk. Further work in capturing detailed information on curved locomotion is needed to understand the adaptation mechanisms used by the horse and the influence of a rider and/or hander to these mechanisms.

Conclusion

From this study it is evident that speed influences adaptation to curved motion, indicating that adaptation is gait specific. Increased duty factor and a larger difference in limb inclination for the inside forelimb on a flat curve suggests this limb may be required to develop more centripetal force at the ground. Generating more centripetal force at the ground increases the rotational moments in the frontal plane, which if unbalanced may increase the risk of injuries to the outside fore and hind limbs. Repetitive overloading closer to the medial and lateral borders due to these frontal plane forces and moments may lead to compression injuries, degenerative joint disease and/or collateral ligament injuries. It appears that the slope allows horses to negotiate the curve with limb posture closer to body posture and probably with demands on the musculoskeletal system more similar to straight canter.

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4 SPSS, Chicago, USA
5 StatSoft Inc., Tulsa, OK, USA.,

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Table 1: Mean (s.d.) speed (m s^{-1}) for 6 horses at walk trot and canter gaits on left and right turns. Number of strides used to calculate the mean for each horse (n).

		Flat		**Banked**	
	n	**Right turn**	**Left turn**	**Right turn**	**Left turn**
Walk*	3-6	1.57 (0.18)	1.51 (0.20)	1.39 (0.10)	1.41 (0.16)
Trot	3-8	3.82 (0.32)	3.64 (0.44)	3.57 (0.26)	3.59 (0.34)
Canter	3-11	4.89 (0.50)	4.68 (0.20)	4.72 (0.43)	4.87 (0.28)

*Indicates significant difference in speed (P<.05) between flat and banked curves independent of rein.

Table 2: Mean (s.d.) stride length (m), duty factor (% stride), McIII, MtIII and relative body inclination (degrees) for 6 horses at walk trot and canter on flat and banked curves. Number of trials used to calculate the mean for each horse (n). Outside and inside legs for each rein are shown separately.

		Flat				**Banked**			
		Right turn		**Left turn**		**Right turn**		**Left turn**	
	n	Outside	Inside	Inside	Outside	Outside	Inside	Inside	Outside
Stride Length (m)									
Walk	3-7	1.8 (0.1)	1.7 (0.2)	1.7 (0.2)	1.8 (0.8)	1.7 (0.2)	1.6 (0.1)	1.6 (0.2)	1.7 (0.2)
Trot	3-9	2.7 (0.2)	2.6 (0.2)	2.6 (0.3)	2.7 (0.3)	2.7 (0.2)	2.6 (0.2)	2.6 (0.3)	2.7 (0.3)
Canter	3-10	2.6 (0.2)	2.5 (0.2)	2.4 (0.3)	2.5 (0.2)	2.7 (0.3)	2.6 (0.3)	2.4 (0.4)	2.7 (0.2)
Duty Factor (% stride)									
Walk	3-7	65.5 (2.3)	65.1 (2.2)	65.7 (1.9)	64.3 (6.5)	68.4 (1.1)	64.9 (1.9)	66.2 (3.0)	67.9 (1.6)
Trot	3-9	42.8 (2.9)	44.5 (1.6)	46.8 (2.9)	43.3 (2.9)	44.2 (2.3)	42.4 (2.2)	43.4 (2.5)	44.1 (3.9)
Canter	3-10	45.5 (4.2)	47.2 (2.6)	47.2 (1.2)	46.0 (2.9)	45.6 (2.7)	43.1 (2.3)	43.6 (3.6)	45.4 (2.6)
McIII inclination (degrees)									
Walk	3-9	-6.5 (0.9)	6.3 (1.9)	8.3 (2.6)	-7.8 (5.3)	-17.3 (1.8)	-1.9 (3.8)	-5.1 (1.4)	-16.4 (3.5)
Trot	4-12	14.5 (6.3)	20.8 (3.9)	20.2 (2.4)	17.3 (4.1)	4.2 (3.3)	9.5 (3.6)	9.3 (4.7)	5.6 (5.4)
Canter	3-14	23.1 (6.8)	31.0 (6.2)	27.6 (4.3)	20.9 (5.8)	16.7 (5.0)	19.1 (5.0)	19.4 (5.1)	15.8 (7.5)
MtIII inclination (degrees)									
Walk	3-11	6.3 (2.8)	5.5 (2.4)	6.9 (2.4)	6.6 (2.1)	-3.8 (2.8)	-2.5 (5.3)	-0.4 (3.0)	-3.4 (3.7)
Trot	3-12	17.8 (5.5)	23.7 (9.3)	21.4 (9.5)	14.3 (3.1)	3.3 (6.2)	14.1 (6.1)	16.9 (9.1)	6.0 (5.3)
Canter	3-15	28.7 (7.4)	30.0 (6.1)	22.5 (5.8)	25.4 (4.9)	16.5 (3.5)	20.9 (7.1)	25.9 (4.8)	20.0 (7.5)
Rel. body inclination (degrees)									
Walk	3-10	5.5 (1.7)	5.8 (2.5)	4.0 (1.5)	8.4 (1.5)	-1.7 (5.0)	-3.3 (3.9)	-2.4 (5.2)	-1.1 (3.8)
Trot	3-12	22.8 (1.4)	16.0 (4.7)	14.0 (6.6)	22.3 (4.9)	10.9 (3.0)	7.8 (4.4)	7.1 (8.6)	12.1 (7.2)
Canter	3-16	30.5 (2.6)	23.5 (6.7)	18.3 (5.6)	26.7 (8.0)	19.0 (5.5)	18.1 (4.0)	13.1 (3.9)	22.7 (7.0)

Table 3: Results of the 2 surface angle (flat vs. banked) by 2 leg (inside vs. outside) ANOVA for the dependent variables stride length, duty factor, McIII inclination, MtIII inclination, trunk inclination and within body angle. In all instances rein did not influence results and are therefore omitted from the analysis. Statistical definitions are as follows; F is the F ratio which is the variance between the groups divided by the variance within the groups, P is the significance and η^2 is the effect size.

	Surface angle (flat vs. bank)			**Leg (inside vs. outside)**			**Interaction surface angle X leg**		
	F	**P**	**η^2**	**F**	**P**	**η^2**	**F**	**P**	**η^2**
Stride Length									
Walk	3.52	.07	.07	4.06	.05*	.08	0.002	.96	.00
Trot	0.01	.98	.00	2.29	.14	.05	.01	.94	.00
Canter	1.22	.28	.03	4.05	.05*	.08	0.22	.64	.01
Duty Factor									
Walk	4.06	.05*	.09	1.59	.21	.04	3.21	.08	.07
Trot	1.11	.30	.03	0.73	.40	.02	6.06	.02*	.12
Canter	6.59	.01**	.13	0.18	.68	.00	4.90	.03*	.10
McIII Inclination									
Walk	143.4	<.001**	.79	265.3	<.001**	.88	0.42	.52	.01
Trot	70.63	<.001**	.64	12.00	.001**	.23	0.01	.97	.00
Canter	22.44	<.001**	.36	9.39	.004**	.19	1.62	.21	.04
MtIII Inclination									
Walk	84.16	<.001**	.69	0.36	.55	.01	2.37	.15	.06
Trot	20.27	<.001**	.34	18.11	<.001**	.31	1.14	.29	.03
Canter	10.53	.002**	.22	1.48	.23	.04	2.77	.10	.07
Relative Body Inclination									
Walk	66.00	<.001**	.62	3.29	.08	.08	0.08	.78	.00
Trot	33.61	<.001**	.46	13.17	.001**	.25	1.19	.28	.03
Canter	17.37	<.001**	.31	17.19	<.001**	.31	0.63	.43	.02

*P ≤ .05; **P < .01

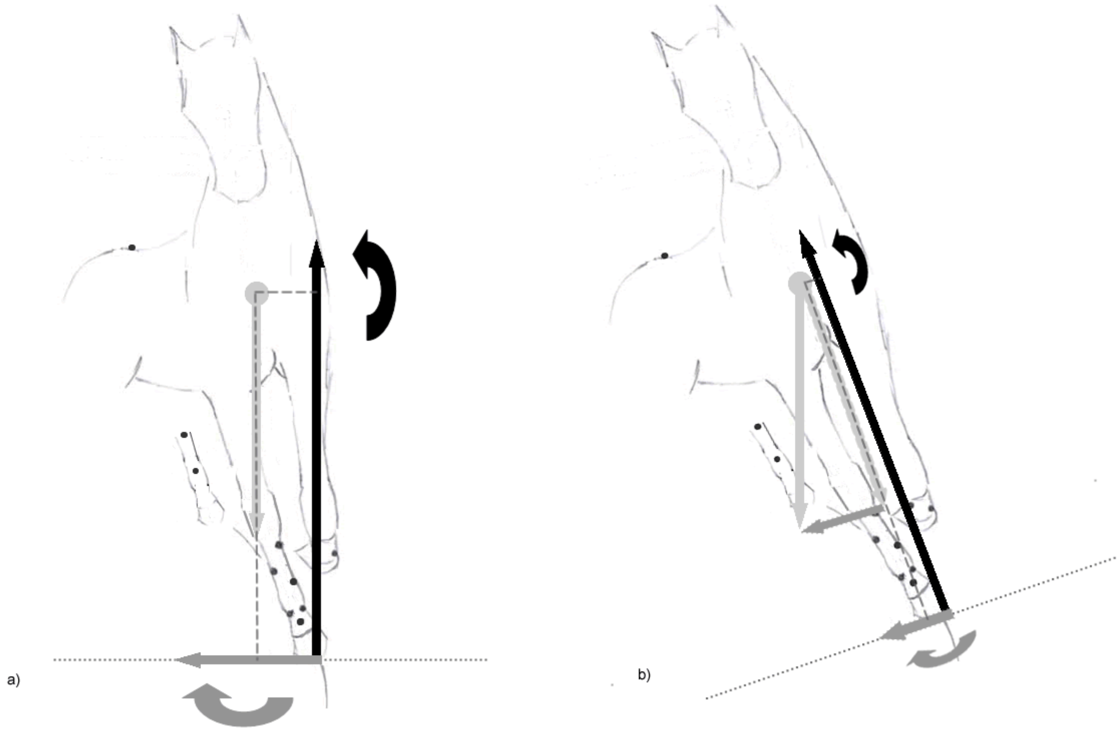
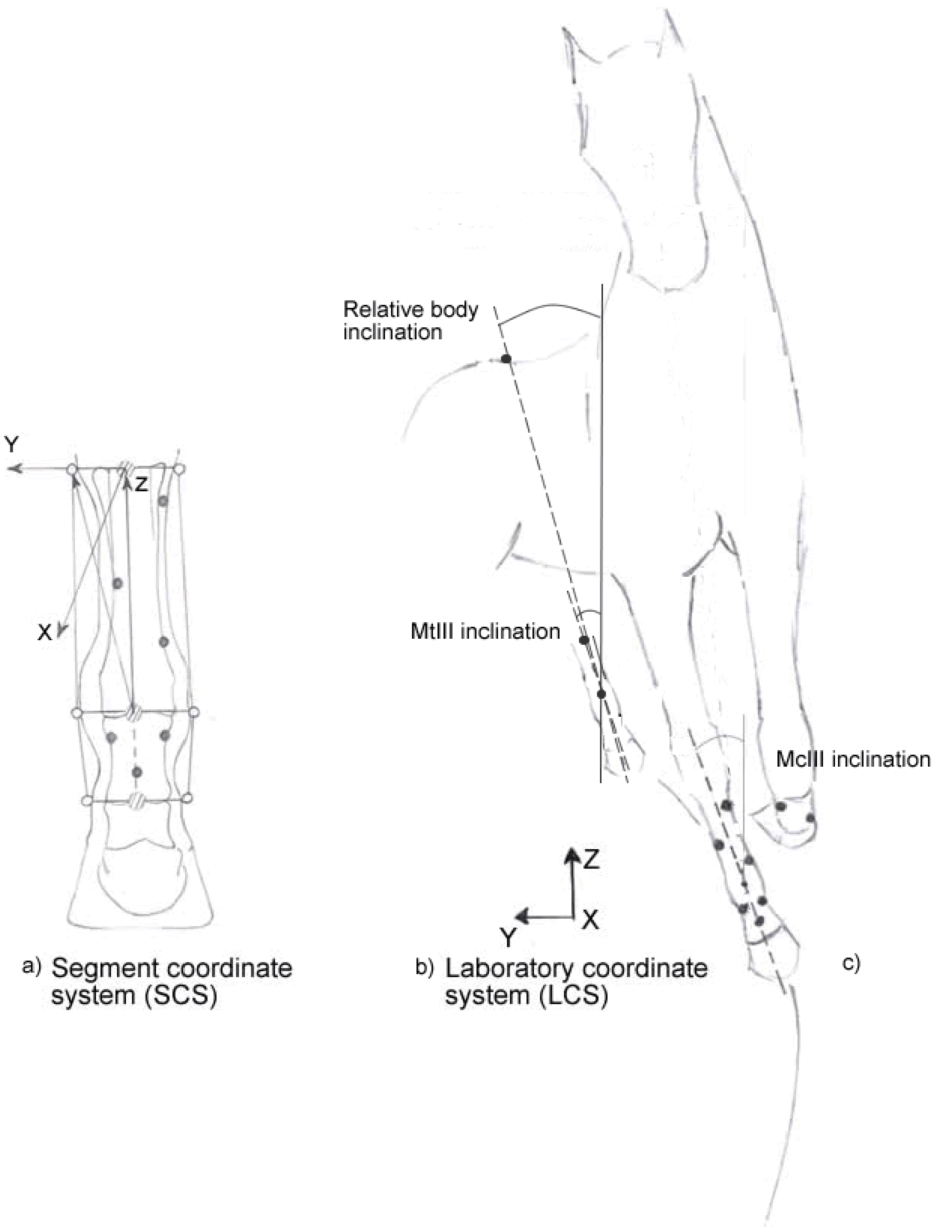


Figure 1: Theoretical GRFs and moments required in the frontal plane to negotiate a) a flat curve and b) a banked curve. In a) the centripetal force (inwardly directed GRF) (grey) is generated at the ground by the horse pushing outwards, which produces a clockwise moment around the centre of mass. The horse leans in, so that the normal GRF (black) is at a distance outside of the circle relative to the centre of mass. The clockwise moment (grey curved arrow) is therefore balanced with an anti-clockwise moment (black curved arrow) when the distance from the centre of mass to the normal GRF multiplied by the normal GRF equals the clockwise moment. In b) not as much centripetal force at the ground is required because a component of body weight (grey) acts down the slope. Consequently, the clockwise moment acting on the centre of mass from the centripetal force at the ground is smaller (grey curved arrow), so the balancing anti-clockwise moment (black curved arrow) is also smaller. The normal GRF (black) also shows the zero position for inclination measurements, which is perpendicular to the bearing surface.


a) Segment coordinate system (SCS)

b) Laboratory coordinate system (LCS)

c)

Figure 2: Definition of; a) the segment coordinate system (SCS) for McIII and PI. The SCS is found by 1) defining segment end points from medial and lateral markers, 2) projecting the z axis from distal to proximal, 3) defining the y-z plane from the distal end point to the proximal lateral marker and using the z axis, 4) projecting the x axis forwards (dorsally), 5) calculating the y axis perpendicular to the x-z plane. The technique is illustrated for McIII. b) The laboratory coordinate system (LCS) (with the Z axis aligned vertically, the Y axis aligned towards the inside of the circle and the X axis aligned in the direction of motion (at a tangent to the circle)), and c) relative body inclination, MtIII and McIII inclination on the flat circle. Inclination is measured from the perpendicular to the bearing surface (vertical for a flat surface and at 10 degrees from the vertical towards the inside of the circle on a banked surface). This definition is similar to what might be described as a varus or valgus angle. For this study, a positive

inclination relates to an angle towards the inside of the circle, a negative inclination relates to an angle towards the outside of the circle. The figure therefore shows positive inclinations of McIII, MtIII and relative body inclination on the flat surface.

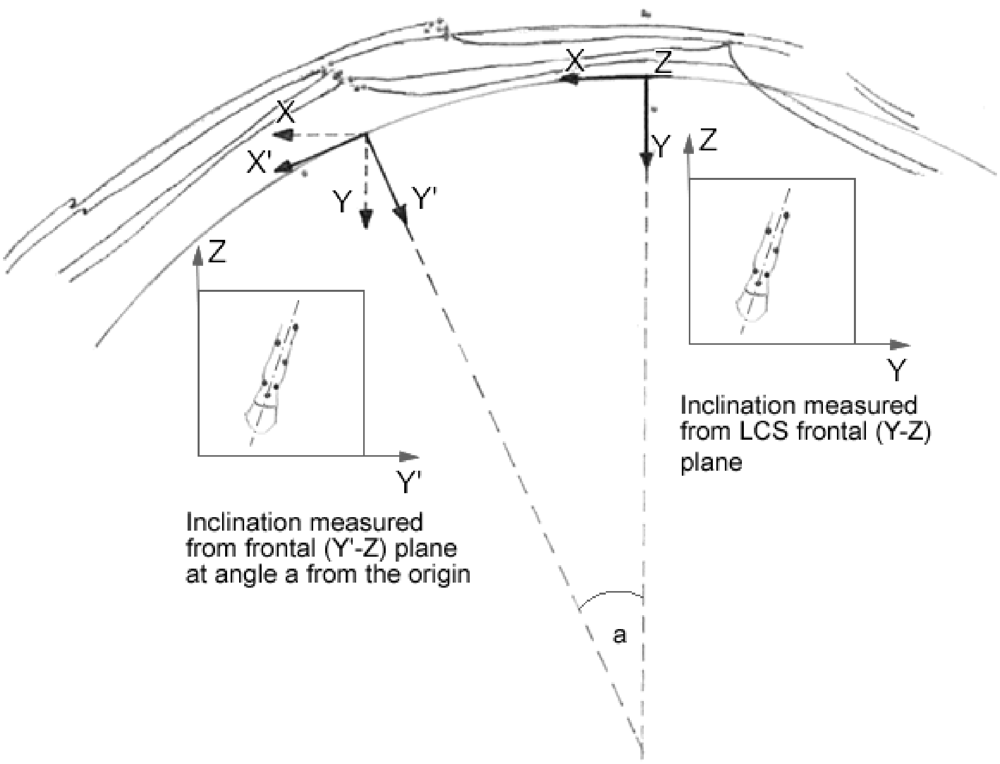


Figure 3: Path of McIII and PI segments from two strides of one horse at canter (lines around the outside of the curve). Also illustrating the frontal plane at the origin of the laboratory coordinate system (LCS) and the frontal plane at left, inside forelimb foot strike at angle, a from the origin of the LCS.