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Three-dimensional kinematics of the equine distal forelimb: effects of a sharp turn at the walk

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Keywords: horse; biomechanics; kinematics; digital joints; walk; circle; turn

Summary

***Reasons for performing study*: Sharp turns are suspected to increase expression of several distal forelimb lamenesses even at the walk but the biomechanical consequences of such a movement remain unknown.**

***Objective*: To quantify the effects of a sharp turn at the walk on the 3-dimensional movements of the distal segments of the forelimb.**

***Methods*: Kinematics of the distal segments were measured in 4 healthy horses invasively with an ultrasonic system. Three-dimensional rotations of the digital joints were calculated by use of a joint coordinate system. Data obtained for a turn at the walk were compared to those obtained in a straight line.**

***Results*: During the stance phase in a turn, the inside forelimb underwent an adduction that induced lateromotion and medial rotation in the distal interphalangeal joint and medial rotation in the proximal interphalangeal joint. These movements were maximal at heel-off and decreased during breakover as the hoof underwent a sudden lateral rotation.**

***Conclusions*: Walking in a sharp turn affects the kinematics of the digital joints outside the sagittal plane.**

***Potential relevance:* This knowledge offers the opportunity to derive hypotheses on biomechanical factors that could contribute to the pathogenesis of digital injuries and on consequences for rational shoeing.**

Introduction

Sharp turns are suspected to increase expression of several distal forelimb lamenesses, even at the walk, and to be a cause or at least a factor in the pathogenesis of a number of digital joint injuries (Hertsch and Beerhues 1988; Dyson 1991; McDiarmid 1998; Denoix 1999). Examination of the horse on a circle at the walk and trot is considered to be useful to characterise a lameness because horses affected with specific digital injuries are often more lame when the involved limb is on the inside of the turn (Swanson 1988). However, there is a lack of kinematic data to understand precisely the articular consequences of displacement in a turn, because kinematic studies are performed mainly in straight lines and are restricted to the measurement of movements in the sagittal plane.

During a turn, especially on a hard surface, alignment between the hoof and the third metacarpal bone is disrupted in the frontal plane and it is probable that the digital joints are the main interface which compensates for this misalignment. Objective data are needed to test this hypothesis and to quantify the relative involvement of each digital joint. Understanding the effects of walking in a circle on digital joint kinematics would be useful to improve our knowledge on the physiology of the joints and on the pathogenesis of several digital injuries. Such data are one of the prerequisites for prevention and treatment of these injuries.

The occurrence of motions outside the sagittal plane in the digital joints has previously been documented *in vitro*. Intra-articular injection of a coloured solution was used to evaluate variations in contact areas between articular surfaces due to asymmetrical placement of the hoof (Denoix 1999). Radiographic assessment has also been proposed (Caudron *et al*. 1998), but this method was limited to the measurement of combined movements between the proximal and distal interphalangeal joints and there was a risk of misinterpretation due to the geometrical projection on a single plane.

A way to measure 3°-of-freedom articular rotations is by definition of orthogonal frames, rigid with the bones and numerically described with an orientation matrix. This has been applied *in vitro* in isolated forelimbs (Degueurce *et al*. 2000). The effects of changes in the transverse orientation of the foot were quantified while the limbs were loaded by use of a power press (Chateau *et al*. 2001, 2002). The angles of flexion/extension, collateromotion (passive abduction/adduction; Denoix 1999) and axial rotation have been calculated by use of the principles of the joint coordinate system (JCS) (Grood and Suntay 1983) applied to the digital joints. Those studies have documented that asymmetrical placement of the foot induced, in the 3 digital joints, a collateromotion (narrowing of the articular space) in the direction of the elevated part of the foot and an axial rotation in the opposite direction. However, *in vitro* studies or quasistatic radiographic studies cannot merely be extrapolated to the moving horse.

To our knowledge, *in vivo* measurements of the biomechanical behaviour of the digital joints have been limited to displacement in a straight line and no objective data are available for movement on a circle. Recently, a method that allows measurement of the 3°-of-freedom rotations in the digital joints of moving horses has been developed and tested *in vivo* (Chateau *et al*. 2004). The objective of the study reported here was to test and quantify the effects of a sharp turn at the walk on 3D rotations of the digital joints.

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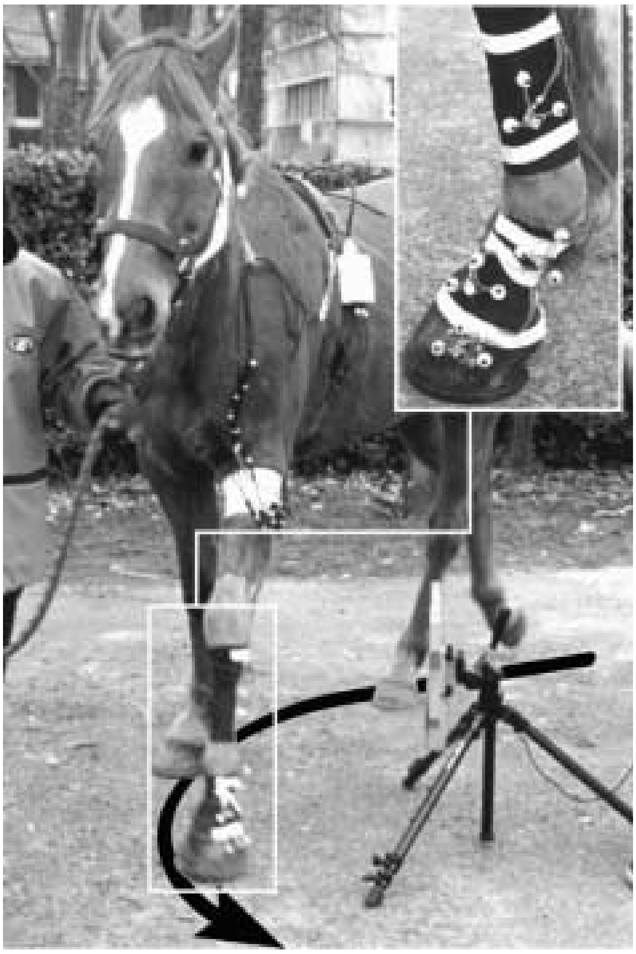

Fig 1: Photograph of the experimental setup. Arrow indicates the movement of the horse in a left turn, on a path that was drawn on the ground. Zoom box shows triads of markers affixed to the tip of the intracortical pins.

Materials and methods

Experimental procedures

The technical background, error analysis and procedures are described in-depth elsewhere (Chateau *et al*. 2004). Briefly, a group of 4 healthy French Trotter geldings (mean ± s.d. age 6 ± 2 years, 495 ± 40 kg bwt) were used. The hooves of both forelimbs on each horse were trimmed by an experienced farrier to a length deemed appropriate for that horse. A ‘geometric limb-axis-oriented’ procedure was used to obtain standard mediolateral balance of the hooves (Balch *et al*. 1991). Because this work was a part of a more comprehensive study, the hooves of both forelimbs were shod with shoes allowing permutation during the experimental sessions (Chateau *et al*. 2004). The weight of such a device was approximately 500 g. The shoes used in the study reported here were standard iron shoes.

Kinematic markers were linked with the underlying bones by use of intracortical pins implanted in the third metacarpal bone and proximal and middle phalanges of the left forelimb. For the distal phalanx, the tip of the pin was welded on a plate that was screwed into the lateral quarter of the hoof wall. Horses were anaesthetised for surgery. The procedures employed were reviewed and approved by the Animal Care Committee of the Direction des Services Vétérinaires (Val-de-Marne, France).

TABLE 1: Temporal variables; mean (s.d.) in a straight line and on a small circle at the walk

	Time (msec)		Time (%)*	
	Straight	Circle	Straight	Circle
Landing (IMP–HS)	64.3 (19.5)	77.7(20.6)†	7.6 (2.5)	7.3 (2.1)
Bearing (HS–HO)	699.8 (66.7)	825.0 (83.7)†	81.8 (3.3)	76.5 (4.9)†
Breakover (HO–TO)	90.6 (15.9)	175.8 (52.5)†	10.6 (1.8)	16.3 (4.7)†
Entire stance (IMP–TO)	854.7 (60.7)	1078.4 (76.5)†	100 (0.0)	100 (0.0)

IMP = impact; HS = hoof stabilisation; HO = heel-off; TO = toe-off; *% of duration of stance phase; †Value differs significantly ($P<0.05$) from the straight line.

Kinematic devices (triads) attached 3 noncollinear kinematic markers with 3 rods. These triads were affixed to the tip of the intracortical pins (Fig 1). Recording procedures were performed by use of the Zebris CMS-HS system[1], based on the determination of the 3D coordinates of miniature ultrasound microphones (markers) whose position relative to a fixed system of 3 ultrasound transmitters was derived from the time delay between the ultrasound pulses, by use of triangulation (Chateau *et al*. 2003). For one trial, the 3D coordinates of the microphones were recorded during a period that covered an entire stance phase. A minimum of 5 trials for each horse and each condition were recorded at a sampling rate of 60 Hz. Horses were led on a hard (asphalt) track. Each horse walked at its own comfortable speed. The reference condition was a displacement in a straight line. The tested condition was a left turn in a small anticlockwise circle (approximately 1.5 m in diameter). The path of the circle was drawn on the ground. During this movement, the equipped left forelimb was on the inside of the turn (Fig 1).

At the end of the test session, a kinematic device that allowed definition and visualisation of the axes of an orthogonal frame was aligned with the relevant anatomical axes of each digital bony segment. This procedure made available the geometric relationship between technical coordinate systems (triads) and anatomically relevant coordinate systems that approximated as closely as possible the symmetry axes of the bones (Chateau *et al*. 2004).

Data processing

Three-dimensional coordinates of the markers were filtered by use of a second order recursive Butterworth low pass filter using a cut-off frequency of 20 Hz.

The kinematics of each digital joint (metacarpophalangeal joint [MPJ], proximal interphalangeal joint [PIPJ] and distal interphalangeal joint [DIPJ]) were resolved in accordance with the convention of the JCS introduced by Grood and Suntay (1983) and adapted to the digital joints of moving horses by Chateau *et al*. (2004). In this Eulerian system, the angle of flexion/extension was measured around the lateromedial axis of the proximal segment, the angle of axial rotation around the proximodistal axis of the distal segment; and the angle of collateromotion around the axis perpendicular to the 2 other axes. The sign convention resulted in lateromotion (passive abduction) and lateral rotation as positive motions (Fig 2a). The palmar joint angle of the PIPJ and DIPJ and the dorsal joint angle of the MPJ were used to describe flexion and extension such that flexion of the MPJ was positive motion whereas flexion of the PIPJ or DIPJ was negative motion.

The attitude angles (pitch, roll and yaw) of the hoof and the third metacarpal bone (McIII) were calculated relative to the global reference frame. Pitch angle was measured around the lateromedial

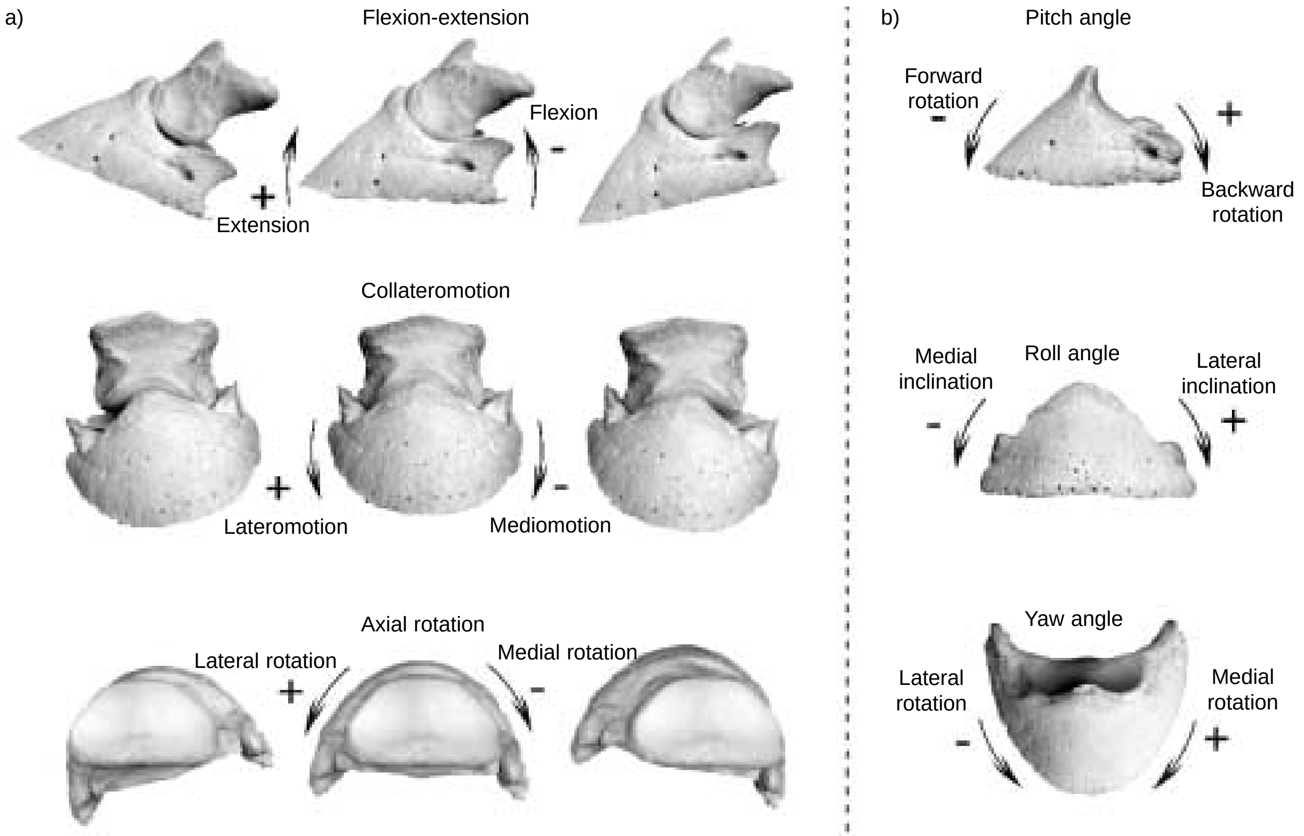

Fig 2: Definition of angles and sign convention for a) the joint angles (example. of the distal interphalangeal joint) and b) the attitude angles of the segments (example of the hoof) in the left forelimb.

axis of the segment, yaw angle around the vertical axis of the global reference frame and roll angle around the axis perpendicular to the 2 other axes. The sign convention adopted backward rotation, lateral inclination and medial rotation as positive motions (Fig 2b). Yaw angle of the third metacarpal bone was not investigated because the large amount of inclination of this segment in the sagittal plane led to misinterpretation of the rotation of this segment around the vertical axis of the global reference frame.

Attitude angles of the hoof were used to detect temporal variables of the stance phase. The stance phase was divided into 3 periods (Chateau *et al*. 2004). The first period was landing, from impact (IMP) to hoof stabilisation (HS). IMP was the first contact of the hoof with the ground. It was detected by cross-checking the 3 variables that defined the orientation of the hoof (i.e. pitch, roll and yaw). Their angle-time diagrams underwent a visible break at impact. HS was defined as the time when pitch, roll and yaw angles of the hoof became invariable. The bearing phase (i.e. strict stance phase) began at HS and ended at heel-off (HO). HO occurred at the beginning of the forward rotation of the hoof (i.e. decrease of pitch angle). The last period was breakover from HO to toe-off (TO). TO was defined as the time when the angular velocity of the forward rotation of the hoof noticeably increased.

Statistical analysis

An ensemble average of all strides for all horses was used to plot average angle curves (± s.e.) vs. time (expressed as percentage of the stance phase from IMP to TO).

The values of each joint angle as well as ranges of motion (ROM) were considered for statistical analysis. An ANOVA was performed to test the effect ($P<0.05$) of condition (turn vs. straight line). For ranges of motion, bounds of the intervals were also compared to test the difference between initial and final values.

Lastly, angular variations (AV) were calculated by subtracting mean joint angles in a straight line from mean joint angles in a turn. AV was expressed as a confidence interval (CI) calculated at a 95% level. Unless otherwise specified, means ± s.d. are reported throughout the text.

Results

Temporal variables

The duration of the stance phase was significantly longer (+224 ± 31 msecs) in a turn than in a straight line (Table 1). The speed of the walk was 1.28 ± 0.09 m/secs in a straight line, and 1.23 ± 0.08 m/secs at the beginning of the turn. In percentage of the stance phase the landing period was not significantly different, but breakover was longer (+5.6 ± 1.9%) because heel-off was proportionally earlier in a turn.

Kinematics in the sagittal plane

During landing in a turn, impact of the hoof was heel first for one horse, toe first for another and flat-footed for the other two; therefore, the resulting mean pitch angle of the hoof underwent no statistically significant trend. On the contrary, landing was

TABLE 2: Ranges of motion; mean (s.d.) during landing, bearing and breakover in a straight line and on a short circle at the walk

		Landing (IMP–HS)		Bearing (HS–HO)		Breakover (HO–TO)	
		Straight line	Circle	Straight line	Circle	Straight line	Circle
Hoof	Pitch	-4.1 (5.4)*	0.4 (6.0)†	0.0 (1.0)	0.4 (1.1)	-9.8 (2.9)*	-8.2 (4.1)*
	Roll	-6.2 (2.7)*	0.7 (3.8)†	-0.6 (0.9)	0.2 (0.8)	1.9 (1.3)*	4.6 (2.8)*†
	Yaw	0.9 (3.7)	-2.4 (4.2)	-0.1 (0.9)	-0.1 (2.6)	-1.3 (4.5)	-11.3 (8.6)*†
McIII	Pitch	-3.7 (1.7)*	-3.5 (1.0)*	-41.0 (4.4)*	-33.6 (3.7)*†	-5.8 (1.4)*	-7.7 (3.0)*†
	Roll	1.2 (1.2)*	-0.6 (1.1)†	-7.5 (5.5)*	7.3 (5.2)*†	-1.5 (1.0)*	-2.7 (1.8)*†
MPJ	Flex-Ext	-10.9 (4.6)*	-12.2 (5.1)*	-0.1 (3.4)	-7.4 (5.9)*†	9.0 (1.9)*	13.4 (3.4)*†
	Collat.	0.2 (1.7)	-0.1 (0.7)	0.3 (0.8)	0.0 (0.7)	-0.3 (0.9)	0.0 (1.0)
	Axial rot	0.2 (0.9)	1.3 (0.7)*†	0.2 (1.3)	-1.1 (0.5)*†	-0.3 (0.8)	0.2 (0.6)
PIPJ	Flex-Ext	0.9 (1.8)	0.9 (4.2)	9.2 (2.4)*	6.5 (2.1)*†	-0.2 (0.6)	1.3 (0.9)*†
	Collat.	-0.6 (1.5)	-0.2 (0.9)	0.4 (1.1)	-0.3 (0.8)	0.5 (0.7)*	0.8 (0.6)*
	Axial rot.	-2.2 (1.1)*	-0.5 (1.3)†	1.1 (1.7)*	-4.0 (1.7)*†	0.6 (0.8)*	2.9 (0.8)*†
DIPJ	Flex-Ext	-12.1 (2.2)*	-9.3 (4.8)*†	33.1 (3.4)*	18.4 (5.9)*†	5.1 (2.5)*	12.3 (4.4)*†
	Collat.	0.9 (2.4)*	-0.4 (2.2)†	-1.9 (1.6)*	2.0 (1.8)*†	-0.3 (0.8)	0.2 (1.1)
	Axial rot.	-1.7 (1.6)*	1.0 (2.0)†	-2.2 (2.5)*	-10.2 (3.9)*†	1.5 (1.6)*	3.6 (1.3)*†

McIII = third metacarpal bone; MPJ = metacarpophalangeal joint; PIPJ = proximal interphalangeal joint; DIPJ = distal interphalangeal joint; IMP = impact; HS = hoof stabilisation; HO = heel-off; TO = toe-off. *Value differs significantly (P<0.05) between the beginning and end of the period. †ROM differs significantly (P<0.05) from the straight line.

TABLE 3: Angular variation and 95% confidence intervals calculated by subtracting the mean angle in a straight line from that in a turn at the walk

	IMP	HS	HO	TO
McIII pitch	**-2.1**†	**-1.9**†	**5.5**†	**3.5**†
	-3.8– -0.4	-3.7– -0.1	4.3–6.7	2.2–4.8
McIII roll	**-8.4**†	**-6.7**†	**8.1**†	**6.9**†
	-10.4– -6.4	-8.4– -5.0	7.6–9.6	5.1–8.7
MPJ axial rot.	**-0.7**†	**0.3**	**-1.0**†	**-0.4**†
	-1.4–0.0	-0.2–0.8	-1.3– -0.7	-0.6– -0.2
PIPJ axial rot.	**0.2**	**1.9**†	**-3.3**†	**-1.0**†
	-0.2–0.6	1.3–2.5	-3.7– -2.9	-1.4– -0.6
DIPJ collat.	**-1.7**†	**-3.0**†	**0.9**†	**1.4**†
	-2.8– -0.6	-3.9– -2.1	0.4–1.4	0.8–2.0
axial rot.	**-0.4**	**2.3**†	**-5.8**†	**-3.7**†
	-1.2–0.4	1.3–3.3	-6.8– -4.8	-4.6– -2.8

For abbreviations see Table 2. †Statistically significant (P<0.05) angular variation between a circle and a straight line.

mostly on the heels followed by a forward rotation of the hoof in a straight line (Table 2; Fig 3). Pitch angle of the third metacarpal bone showed less protraction at impact and less retraction at heel-off in a turn (Table 3). Maximal extension of the MPJ was not significantly different between a straight line and a turn, whereas maximal flexion of the DIPJ decreased in a turn (mean AV 3.7; 95% CI 2.6–4.8), as did maximal extension of the PIPJ (mean AV -0.8; 95% CI -1.1– -0.5) and maximal extension of the DIPJ (mean AV -2.0; 95% CI -2.6– -1.4) (Fig 4).

Kinematics outside the sagittal plane

Landing: In a straight line, impact of the foot was invariably on the lateral side of the hoof and was followed by a medial rocking motion that preceded complete stabilisation of the hoof. This lateral impact occurred with the distal limb globally adducted, resulting in a preferential exposition of the lateral aspect of the hoof (Chateau *et al*. 2004). In a turn, roll angle of the third metacarpal bone showed that the distal limb was substantially more abducted at impact (Fig 3). Landing was concurrently flat-footed, with few subsequent rocking motions of the hoof.

During landing in a straight line, the DIPJ underwent a lateromotion and a medial rotation associated with the medial rocking motion of the hoof (Table 2). Conversely, during flat-footed landing in a turn, the DIPJ underwent no significant movement of collateromotion or axial rotation (Table 2). A medial rotation of the PIPJ also occurred during landing in a straight line while axial rotation was not significant at the same point in a turn.

Bearing: No significant movement of the hoof was measured during the bearing phase. Whereas the hoof was immobile on the ground, the third metacarpal bone underwent large movements in the transverse plane in a turn. In a straight line, the third metacarpal bone tended to be adducted at the beginning of the bearing phase and then underwent an abduction until HO (Fig 3). Conversely, in a left turn, the left metacarpal bone was substantially more abducted at HS and, from this attitude, underwent an adduction until HO. At HO, the McIII was therefore more adducted in a turn than in a straight line (Table 3).

In a straight line, a mediomotion of the DIPJ (ROM 1.9 ± 1.6) occurred during abduction of the McIII whereas, in a left turn, a lateromotion of the DIPJ (ROM 2.0 ± 1.8) occurred during adduction of the McIII. At HS, the DIPJ was more in a mediomotion position (Table 3) in a turn than in a straight line and, at HO, more in a lateromotion position. Concurrently, the DIPJ underwent substantial medial rotation (ROM 10.2 ± 3.9°) during the bearing phase in a turn. Compared to a straight line, the joint was laterally rotated at HS and medially rotated at HO (Fig 4).

The PIPJ also underwent medial rotation (Table 2) during the bearing phase in a turn, with the same behaviour as the DIPJ (i.e. lateral rotation at HS and medial rotation at HO). The MPJ was also medially rotated at HO (Table 3). This movement occurred during the second half of the stance phase, i.e. during MPJ flexion (Fig 4).

Breakover: During breakover, a large lateral rotation of the hoof (Table 2) occurred concurrently with lift-off of the heels in a turn, whereas no significant amount of yaw motion was measured in a straight line (Fig 3). At the same time, a lateral rocking motion of the hoof occurred in a turn as well as in a straight line, the medial side of the hoof leaving the ground first.

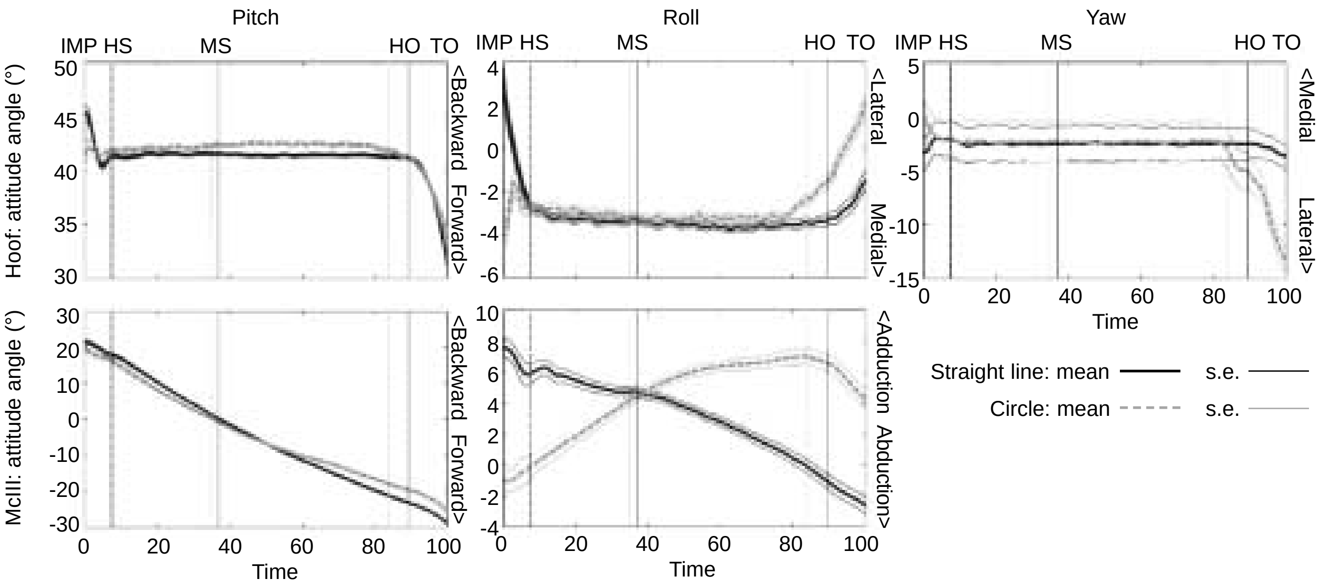

Fig 3: Mean ±s.e. curves of the attitude angles (°) of the hoof and third metacarpal bone (McIII) plotted against time (expressed as % of the stance phase). IMP = impact; HS = hoof stabilisation; MS = mid-stance; HO = heel-off; TO = toe-off.

The lateral rotation of the hoof during breakover in a turn was associated with a sudden lateral rotation of both the distal and proximal interphalangeal joints (Table 2). This movement contributed to the realignment of the distal segments that were medially rotated at the end of the bearing phase.

Discussion

Although the pathogenesis of several digital injuries is believed to be connected with extrasagittal movements of the joints, no quantitative data are available to describe 3D motions of the digital joints when horses are moving on a circle. The present study uses an original method to quantify these movements *in vivo* and provides a comprehensive description of the kinematics of the digital joints in a turn at the walk.

Methodological background

The measuring system (Chateau *et al*. 2003) and the procedures and error analysis (Degueurce *et al*. 2000; Chateau *et al*. 2004) have been described and analysed elsewhere. The kinematic analysis system ZEBRIS-CMS-HS[1] was used to calculate the 3D coordinates of the markers. The precision of this system was evaluated in a preliminary study (Chateau *et al*. 2003). In the same experimental conditions, the standard deviation of theoretically invariable angle between markers of a same triad was 0.5° (Chateau *et al*. 2004).

The use of the JCS, in accordance with the recommendations of the International Society of Biomechanics (Wu and Cavanagh 1995), allowed us to quantify 3 anatomical rotations in the digital joints. Particular attention was needed to establish reliable and reproducible anatomical axes of rotation in order to reduce chance of cross-talk drift. Axes of rotation were defined using a special methodological step analysed in a previous report (Chateau *et al*. 2004), which revealed a mean inaccuracy of 1.4° in the reproducibility of axes alignment. This small inaccuracy shifted to some extent the absolute value of angles, but preserved the pattern of joint motions. It was therefore more reliable to report ranges of motion and relative values than absolute values of angles.

Experimental procedures

An invasive method was used because the movements of surface markers stuck on the skin do not represent the true movement of the underlying bone and may produce large artefacts that counteract the rigid body theory. Several kinematic studies have used bone pins implanted in man (Ramsey and Wretenberg 1999), as well as in horses (van Weeren and Barneveld 1986; Dyhre-Poulsen *et al*. 1994; Lanovaz *et al*. 2002). Special attention was paid to minimise the invasiveness of the procedure, thereby preserving horses from any pain, and no horse revealed lameness during the experiments.

For ethical reasons, it was decided that we should limit the number of subjects to 4 horses. Therefore, generalisation from the results should be considered with some caution. Kinematics of the digital joints and alterations observed in a turn were nevertheless very similar for the 4 horses, with little between-subject variability.

Although the speed of the walk at the beginning of the turn was not significantly different from the speed in a straight line, the sharpness of the turn probably contributed to a progressive decrease of speed on the circle. The duration of the stance phase was longer in a turn. This significant difference must therefore be considered when interpreting the results.

Effects of walking in a circle on 3D kinematics of the distal forelimb

In the sagittal plane, maximal extension of the MPJ was not significantly different between a turn and a straight line, whereas maximal flexion and extension of the PIPJ and DIPJ decreased in a turn, as did protraction and retraction of the limb. However, speed is also likely to be a factor in these results.

The transverse inclination of the third metacarpal bone during turns deeply affects the kinematics of the digital joints outside the sagittal plane. In a turn, the inside forelimb is abducted at the beginning of the stance phase because the horse spreads the inside

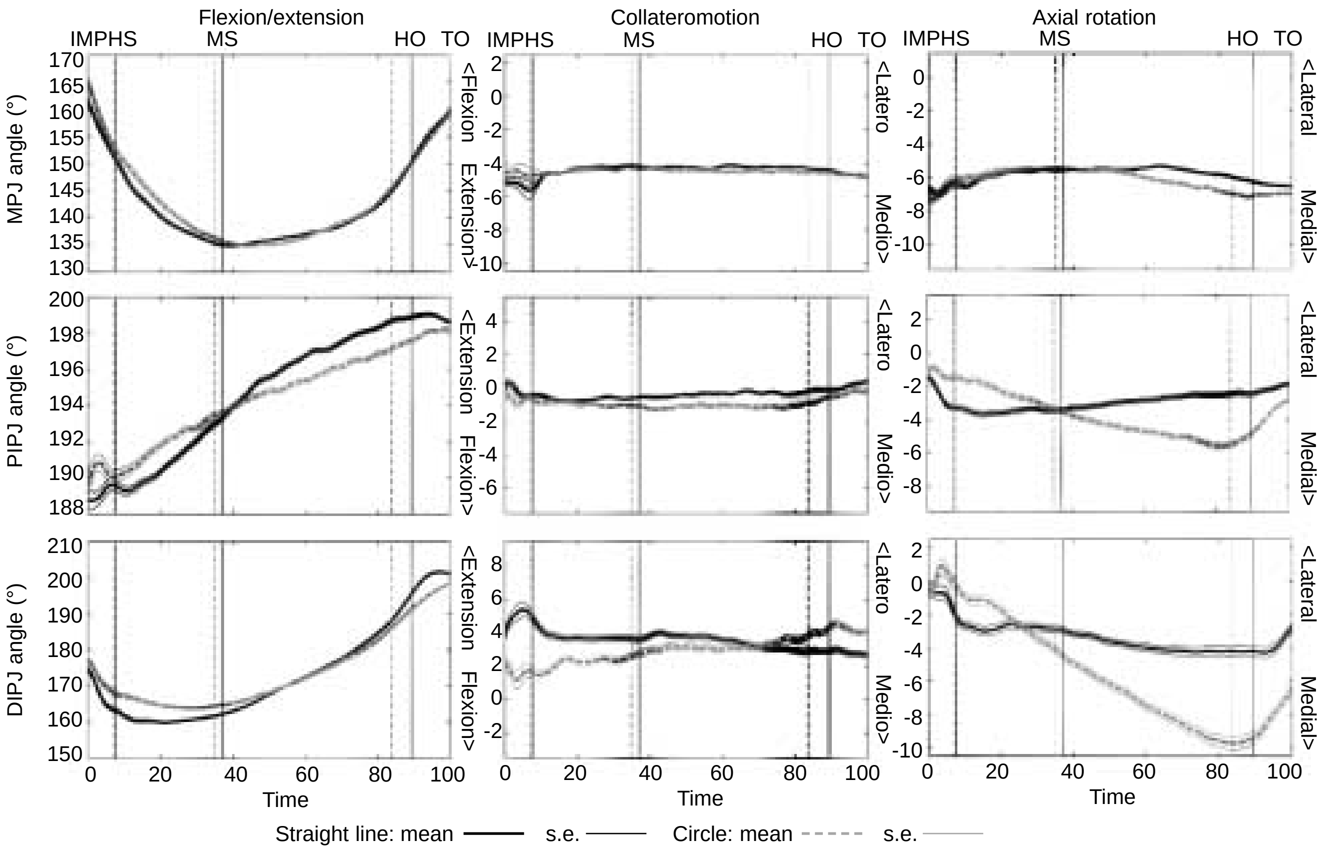

Fig 4: Mean ± s.e. curves of the joint angles (°) plotted against time (expressed as % of the stance phase). MPJ = metacarpophalangeal joint; PIPJ = proximal interphalangeal joint; DIPJ = distal interphalangeal joint; IMP = impact; HS = hoof stabilisation; MS = mid-stance; HO = heel-off; TO = toe-off; Medio = mediomotion; Latero = lateromotion.

forelimb to cover ground in the direction of the movement. During the rest of the bearing phase, the inside forefoot is immobile on the ground and the horse brings the body mass over this limb, in the direction of the turn. In this movement, the limb undergoes an adduction that reaches its maximum when the heels leave the ground. This adduction, while the hoof stays static on the ground, induces deep alterations in the 3D kinematics of the digital joints. The larger alterations were measured in the distal interphalangeal joint which underwent, during the bearing phase, combined movements of lateromotion (2.0 ± 1.8°) and medial rotation (10.2 ± 3.9°). This means that, during this movement, the articular space becomes pinched laterally and the distal phalanx rotates medially relative to the middle phalanx. Collateromotion occurs in the direction of the movement, while axial rotation occurs in the opposite direction. Interestingly, this combination of articular movements was also observed *in vitro* during asymmetrical loading of the limb (Caudron *et al*. 1998; Denoix 1999; Chateau *et al*. 2002; Viitanen *et al*. 2003). The present *in vivo* results support preliminary outcomes and corroborate the reliability of these *in vitro* protocols. Most of these *in vitro* studies were, however, restricted to analysis of the midstance phase because of technical constraints. The present *in vivo* experiment gives information on the whole stance phase. Compared to a straight line, the 3D behaviour of the interphalangeal joints was different at the beginning and end of stance phase. Because the third metacarpal bone was more abducted at the beginning of the stance phase in a turn, the DIPJ was initially in an attitude that associated mediomotion and lateral rotation, compared to a straight line. From this attitude, adduction of the limb reversed the trend. At the end of the stance phase, the DIPJ reached an attitude that associated lateromotion and medial rotation. This phenomenon is easily readable on the angle-time diagrams of collateromotion and axial rotation of the DIPJ as the curves intersect (Fig 4). Such a behaviour should be considered during examination of a lame horse on a short circle at the walk because the cranial and caudal parts of the stance phase do not have the same biomechanical consequences on the interphalangeal joints.

The involvement of the PIPJ was substantial. This joint underwent medial rotation during the bearing phase in a turn. At HO, the PIPJ contributed 33% of the total amount of axial rotation in the digital joints (vs. 10% for the MPJ and 57% for the DIPJ). In this joint, the amount of axial rotation was higher than the amount of flexion. In addition, this increase of axial rotation in a turn was associated with a decrease of flexion and extension, probably due to the tightening of the soft tissues surrounding the articular space. This demonstrates the strong involvement of this joint in movements that occur outside the sagittal plane. These results corroborate clinical observations related to pathological conditions of this joint. Clinical studies (Stashak 1987; Schaer *et al*. 2001) have documented that degenerative diseases of the PIPJ occur most frequently in horses that make short turns and rapid twisting movements. Injuries include pulling or tearing of the joint capsule attachment and collateral ligament attachments (McIlwraith and Goodman 1989). Such a biomechanical behaviour may explain why long-term radiographic evaluation after arthrodesis of this joint often reveals degenerative disease involving the DIPJ or even navicular disease (Martin *et al*. 1984; MacLellan *et al*. 2001). Decreased range of motion due to PIPJ arthrodesis may have exacerbated stresses on the DIPJ and navicular apparatus. The physiological importance of this joint should be kept in mind when such a treatment is considered, and indication of PIPJ arthrodesis should be assessed carefully.

In a turn, extrasagittal stress in the interphalangeal joints was maximal at the end of the bearing phase, because adduction of the limb was greatest at HO. Weight removal from the palmar part of the foot allows the heels to lift off and the hoof to rotate laterally on the ground. This movement of the hoof contributes to the sudden realignment of the pastern, with an apparent decrease of interphalangeal rotations. These results suggest hypotheses on shoeing, because it is probable that delaying breakover or increasing the lever arm on the lateral quarter of the shoe would exacerbate extrasagittal stresses in the interphalangeal joints. Further studies are therefore needed to test whether shoes with a lateral bevel edge would shorten the lever arm and facilitate breakover in a turn.

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References

Balch, O., White, K. and Butler, D. (1991) Factors involved in the balancing of equine hooves. *J. Am. vet. med. Ass*. **198**, 1980-1989.

Caudron, I., Grulke, S., Farnir, F., Aupaix, R. and Serteyn, D. (1998) Radiographic assessment of equine interphalangeal joints asymmetry: articular impact of phalangeal rotations (Part 1). *J. vet. med. Ass.* **45**, 319-325.

Chateau, H., Degueurce, C. and Denoix, J.-M. (2004) Evaluation of three-dimensional kinematics of the distal portion of the forelimb in horses walking in a straight line. *Am. J. vet. Res*. **65**, 447-455.

Chateau, H., Girard, D., Degueurce, C. and Denoix, J.-M. (2003) Methodological considerations for using a kinematic analysis system based on ultrasonic triangulation. *Innovation Technol. Biol. Méd.* **24**, 69-78.

Chateau, H., Degueurce, C., Jerbi, H., Crevier-Denoix, N., Pourcelot, P., Audigié, F., Pasqui-Boutard, V. and Denoix, J.-M. (2001) Normal three-dimensional behaviour of the metacarpophalangeal joint and the effect of uneven foot bearing. *Equine vet. J., Suppl*. **33**, 84-88.

Chateau, H., Degueurce, C., Jerbi, H., Crevier-Denoix, N., Pourcelot, P., Audigié, F., Pasqui-Boutard, V. and Denoix, J.-M. (2002) Three-dimensional kinematics of the equine interphalangeal joints: articular impact of asymmetric bearing. *Vet. Res*. **33,** 371-382.

Degueurce, C., Chateau, H., Pasqui-Boutard, V., Pourcelot, P., Audigié, F., Crevier-Denoix, N., Jerbi, H., Geiger, D. and Denoix, J.-M. (2000) Concrete use of the joint coordinate system for the quantification of articular rotations in the digital joints of the horse. *Vet. Res*. **31**, 297-311.

Denoix, J.-M. (1999) Functional anatomy of the equine interphalangeal joints. *Proc. Am. Ass. equine Practnrs*. **45**, 174-177.

Dyhre-Poulsen, P., Smedegaard, H.H., Roed, J. and Korsgaard, E. (1994) Equine hoof function investigated by pressure transducers inside the hoof and accelerometers mounted on the first phalanx. *Equine vet. J*. **26,** 362-366.

Dyson, S.J. (1991) Lameness due to pain associated with the distal interphalangeal joint: 45 cases. *Equine vet. J*. **23**, 128-135.

Grood, E.S. and Suntay, W.J. (1983) A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J. Biomech. Eng*. **105**, 136-144.

Hertsch, B. and Beerhues, U. (1988) Der Wendeschmerz als Symptom bei der Lahmheitsuntersuchung des Pferdes - Pathomorphologische, röntgenologische und klinische Untersuchungen. *Pferdeheilkunde* **4**, 15-22.

Lanovaz, J.L., Khumsap, S., Clayton, H.M., Stick, J.A. and Brown, J. (2002) Three-dimensional kinematics of the tarsal joint at the trot. *Equine vet. J., Suppl*. **34**, 308-313.

MacLellan, K.N., Crawford, W.H. and Macdonald, D.G. (2001) Proximal interphalangeal joint arthrodesis in 34 horses using two parallel 5.5-mm cortical bone screws. *Vet. Surg*. **30**, 454-459.

Martin, G.S., McIlwraith, C.W., Turner, A.S., Nixon, A.J. and Stashak, T.S. (1984) Long-term results and complications of proximal interphalangeal arthrodesis in horses. *J. Am. vet. med. Ass*. **184**, 1136-1140.

McDiarmid, A.M. (1998) Distal interphalangeal joint lameness in a horse associated with damage to the insertion of the lateral collateral ligament. *Equine vet. Educ*. **10**, 114-118.

McIlwraith, C.W. and Goodman, N.L. (1989) Conditions of the interphalangeal joints. *Vet. Clin. N. Am.: Equine Pract*. **5**, 161-178.

Ramsey, D.K. and Wretenberg, P.F. (1999) Biomechanics of the knee: methodological considerations in the *in vivo* kinematic analysis of the tibiofemoral and patellofemoral joint. *Clin. Biomech.* **14**, 595-611.

Schaer, T.P., Bramlage, L.R., Embertson, R.M. and Hance, S. (2001) Proximal interphalangeal arthrodesis in 22 horses. *Equine vet. J*. **33**, 360-365.

Stashak, T.S. (Ed.) (1987) Lameness. In: *Adam's Lameness in Horses*, 4th edn., Lea & Febiger, Philadelphia. pp 486-785.

Swanson, T.D. (1988) Degenerative disease of the proximal interphalangeal (pastern) joint in performance horses. *Proc. Am. Ass. equine Practnrs*. **34**, 393-397.

van Weeren, P.R. and Barneveld, A. (1986) A technique to quantify skin displacement in the walking horse. *J. Biomech*. **19**, 879-883.

Viitanen, M.J., Wilson, A.M., McGuigan, H.R., Rogers, K.D. and May, S.A. (2003) Effect of foot balance on the intra-articular pressure in the distal interphalangeal joint *in vitro*. *Equine vet. J.* **35**, 184-189.

Wu, G. and Cavanagh, P.R. (1995) ISB recommendations for standardisation in the reporting of kinematic data. *J. Biomech.* **28**, 1257-1261.