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Joint moments in the distal forelimbs of jumping horses during landing

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Summary

Tendon injuries are an important problem in athletic horses and are probably caused by excessive loading of the tendons during demanding activities. As a first step towards understanding these injuries, the tendon loading was quantified during jump landings. Kinematics and ground reaction forces were collected from the leading and trailing forelimbs of 6 experienced jumping horses. Joint moments were calculated using inverse dynamic analysis. It was found that the variation of movement and loading patterns was small, both within and between horses. The peak flexor joint moments in the coffin and fetlock joints were larger in the trailing limb (-0.62 and -2.44 Nm/kg bwt, respectively) than in the leading limb (-0.44 and -1.93 Nm/kg bwt, respectively) and exceeded literature values for trot by 82 and 45%. Additionally, there was an extensor coffin joint moment in the first half of the stance phase of the leading limb (peak value 0.26 ± 0.18 Nm/kg bwt). From these results, it was concluded that the loading of the flexor tendons during landing was higher in the trailing than in the leading limb and that there was an unexpected loading of the extensor tendon in the leading limb.

Introduction

Forelimb tendon injuries are an important problem in athletic horses and are generally assumed to be caused by high or repetitive loading of the tendons. However, relatively little is known about the actual loading of the tendons during demanding activities. The direct measurement of tendon forces is limited by the invasive character of these measurements. Inverse dynamic analysis, however, provides opportunities for noninvasive estimation of tendon loading (Elftman 1939; Meershoek and van den Bogert 2000). For this analysis the limb is modelled as a chain of rigid segments, which can rotate relative to each other. The loading of the tendons is summarised to a net joint moment at each joint. This moment is calculated from externally measured movements and forces (e.g. ground reaction force, GRF) and equals force times moment arm (perpendicular distance between the tendon and the joint centre of rotation) summed over all tendons and ligaments. Inverse dynamic analysis cannot differentiate between individual tendons but it can be used to identify activities with high tendon loading and to evaluate the influence of different conditions (e.g. surface properties, technique of a rider) on tendon loading.

Inverse dynamic analysis has been applied to equine walk and trot (Clayton *et al.* 1998; Colborne *et al.* 1998). Stereotypical joint moment patterns, with small interindividual variation, have been described. During the stance phase of walk and trot there are only flexor joint moments in the distal limb. This indicates that the flexor tendons are loaded during the stance phase, whereas the extensor tendons are loaded only during the swing phase. It is not known whether this is also true during other activities. Furthermore, it is not known whether flexor tendon loads are higher during more demanding activities, like jumping.

Equine jumping is an asymmetrical activity during which the contralateral limbs are used differently. The leading forelimb is placed later and more forward than the trailing forelimb. This difference in placement is probably accompanied by a difference in tendon loading. Schamhardt *et al.* (1993) found differences in GRF between the limbs. However, interindividual variation was high, probably because inexperienced jumpers were used. Furthermore, GRF is an external force that does not necessarily represent joint moments. In human jumping, for instance, there were 2-fold differences in GRF between take-off and landing without differences in knee joint moments (Richards *et al.* 1996). Therefore, tendon loading cannot be determined from GRF measurements only, but should be estimated using inverse dynamic analysis.

Quantification of tendon loading during demanding activities is the first step towards understanding of tendon injuries. The purpose of this study was to describe the joint moments during jump landings and to investigate whether (1) there are only flexor moments and no extensor moments during the stance phase, (2) moments are different between leading and trailing limb and (3) moments during jump landings exceed those during trot. Kinematics and GRFs were measured externally from

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[¶] During preparation of the manuscript, Dr Henk C. Schamhardt sadly passed away.

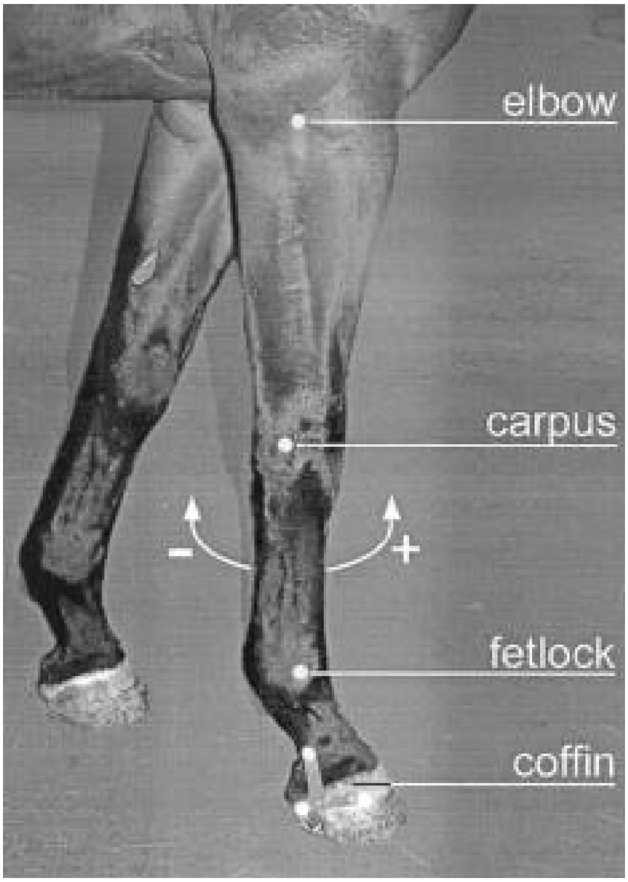

Fig 1: Forelimb with markers (see text). Flexion is defined as negative for all joints.

experienced horses jumping a 1 m fence. Inverse dynamic analysis was used to calculate joint moments in the coffin, fetlock and carpal joints of the leading and trailing forelimb.

Materials and methods

Horses

Six experienced jumping horses and 3 riders, all competing at an intermediate to advanced international level, participated in the experiments. Height at the withers and body mass of the horses were (mean ± s.d.) 1.69 ± 0.05 m and 599 ± 52 kg, respectively; body mass of the riders was 74 ± 14 kg. Each horse was ridden by one rider only.

Jumping protocol

The horses jumped a single vertical fence with a height of 1 m. The position of the fence was adjusted to ensure landing of either the leading or the trailing forelimb on the force plate. Attempts were made for at least 5 successful trials for both leading and trailing forelimbs. A jump was considered successful if (1) the horse cleared the fence, (2) the horse landed with the hoof entirely on the force plate and (3) no other hooves touched the plate simultaneously. The experiments were sometimes discontinued due to fatigue, resulting in fewer trials. The lead, right or left, depended upon the horse's preference. In 3 horses, all measurements were obtained with the same lead but from different limbs (e.g. leading left limb and trailing right limb), whereas in the other 3 horses the measurements were obtained with different leads but from the same limb (e.g. leading right limb and trailing right limb).

Data recording

Forelimb movements were measured using a 3 camera, 240 Hz video-based motion analysis system (ProReflex)[1]. Retroreflective spherical markers, diameter 9 mm, were attached to the skin covering the centres of rotation of the elbow (lateral epicondyle of the humerus), carpus (proximopalmar part of the ulnar carpal bone) and fetlock joint (site of attachment of the collateral ligament, Leach and Dyson 1988) (Fig 1). Three additional markers were attached to a lightweight plastic triangle, which was screwed to the hoof. A lateral radiograph of the hoof was used to determine the centre of rotation of the coffin joint and the orientation of the dorsal hoof wall relative to the hoof markers. The cameras of the motion analysis system were placed around the force plate at a distance of about 2 m. The calibrated volume, centred around the force plate, was about 2 m long, 1 m wide and 1.5 m high.

The GRFs were measured using a force plate (Type 6090-15)[2] and sampled at a sampling frequency of 2400 Hz. The position of the force plate in the coordinate system of the motion analysis system was determined by putting 4 markers on the corners of the plate. The force data were synchronised with the motion data using an electronic pulse from the cameras of the motion analysis system. The force plate and runway were covered with a 4 cm thick sand layer to create a natural jumping surface. This sand did not influence the accuracy of the measurements, because any differences between the force acting on the hoof and the force measured by the force plate would have resulted in accelerations of the sand. The difference in force should equal mass times acceleration of the sand, which was negligible. Furthermore, the height of the hoof above the force plate was needed to calculate the point of application of the GRF. Due to the sand, this height was variable and not known exactly. Instead of using the actual point of application at the hoof surface, the (horizontal and vertical) coordinates of the point of application at the plate surface were used. This did not influence the final results, because the outcome of inverse dynamic analysis depends only on the line of action of the GRF and is not influenced by displacement of the point of application along this line.

Data processing and statistics

Systematic errors in the point of application of the GRF were corrected with plate-specific correction values (Bobbert and Schamhardt 1990). The GRF data were low-pass filtered (4th order, 100 Hz recursive Butterworth filter) and resampled at 240 Hz. Forward and upward GRFs were defined as positive. The stance phase was defined as the time during which the vertical GRF exceeded 1000 N, because the point of application of the GRF cannot be measured accurately at lower forces. Both kinematics and GRFs were normalised to 100% stance phase duration and were projected on a sagittal plane. For each horse, the trials of each limb were averaged.

Joint angles were calculated from the lines connecting the joint centres of rotation. For the hoof segment, a line through the coffin joint centre of rotation and parallel to the dorsal hoof wall was used. Standard anatomical flexion was defined

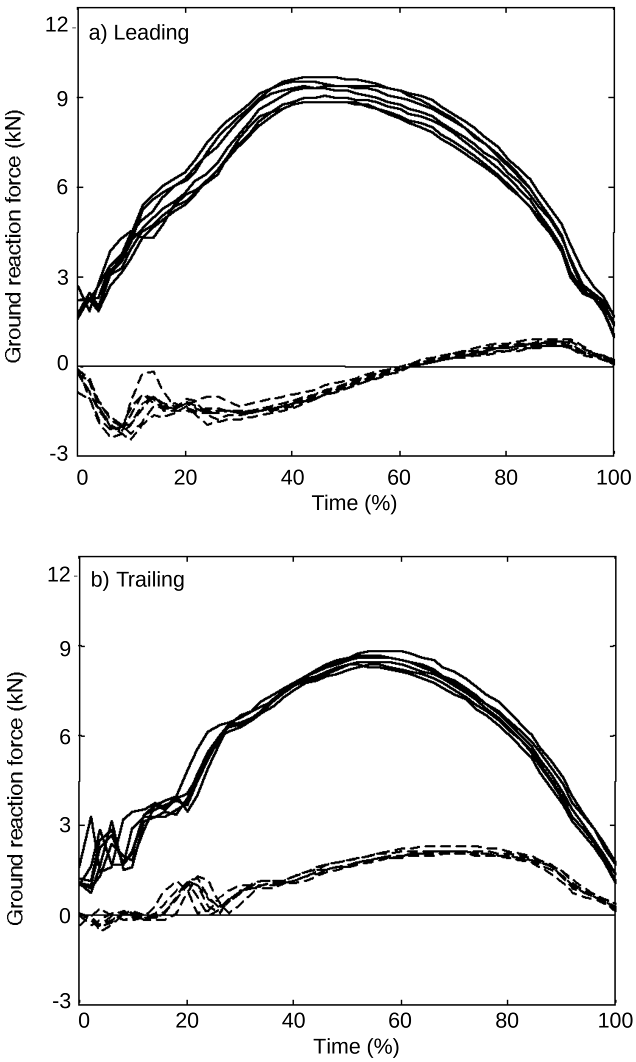

Fig 2: Fore-aft (dashed line) and vertical (solid line) ground reaction forces on the leading (a) and trailing (b) limb during landing; repeated measurements of one horse.

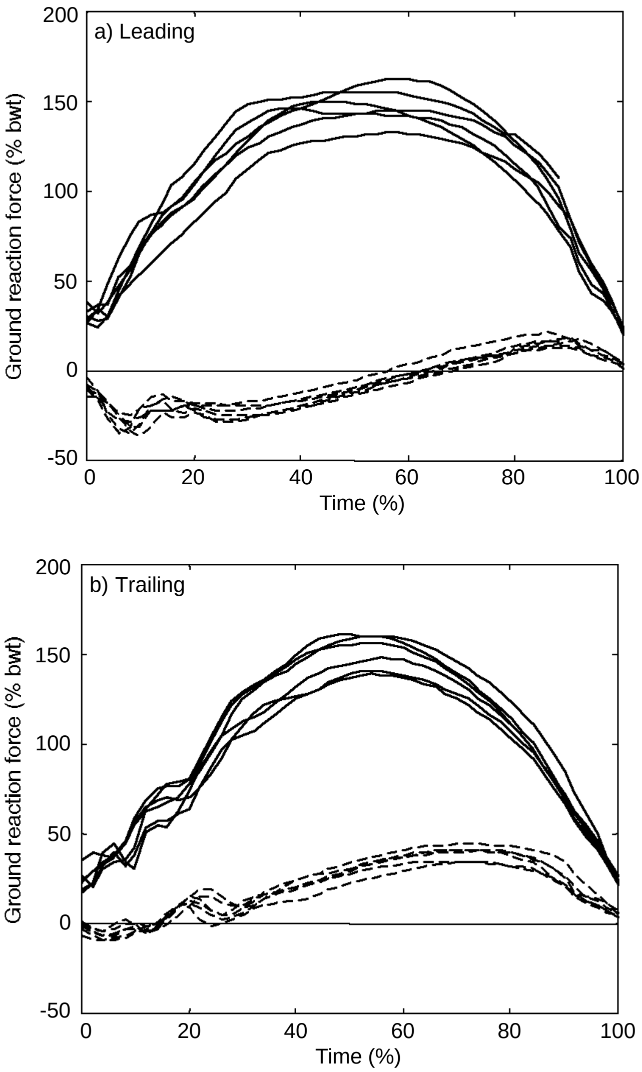

Fig 3: Fore-aft (dashed line) and vertical (solid line) ground reaction forces on the leading (a) and trailing (b) limb during landing; average curves of individual horses.

as negative for both angles and moments (Fig 1). Segmental inertial properties were obtained from Buchner *et al.* (1997). Accelerations were calculated from the averaged and unfiltered position data using a 3 point finite difference routine and net joint moments were calculated using standard inverse dynamic methods (Elftman 1939; Meershoek and van den Bogert 2000).

The force and moment data were normalised to body mass. The trailing limb data of the different horses were averaged regardless of which limb (right or left) was used. The same was done for leading limb data. Student *t* tests were used to test whether differences in peak joint moments between leading and trailing limb were statistically significant ($P<0.05$).

Results

Intra- and interindividual variation

Within each horse, the jump to jump variation of the GRF was small, as can be seen from the superimposed patterns of individual jumps in Figure 2. Between horses, the variation of the GRF was also small, as can be seen from average patterns of each horse superimposed in Figure 3. The other variables, joint angles and joint moments, showed similarly small variation (see s.d. in Fig 5 and Table 1). Because of this small variation, it seems justified to average the data both within one horse and between horses.

Movement pattern

Both leading and trailing limb were almost completely extended at touchdown (Fig 4). The trailing limb was placed almost vertically, whereas the leading limb was placed with the hoof in front of the elbow and slid forward in early stance. The joint angles showed similar patterns in both limbs, although there were some differences in range of motion (Fig 5). The coffin joint was flexed during the major part of the stance phase and hyperextended during final stance. The fetlock joint was hyperextended during the whole stance phase with peak amplitude at 55–65% of stance phase. The carpal joint was hyperextended with nearly constant amplitude (± 10°) during most of the stance phase.

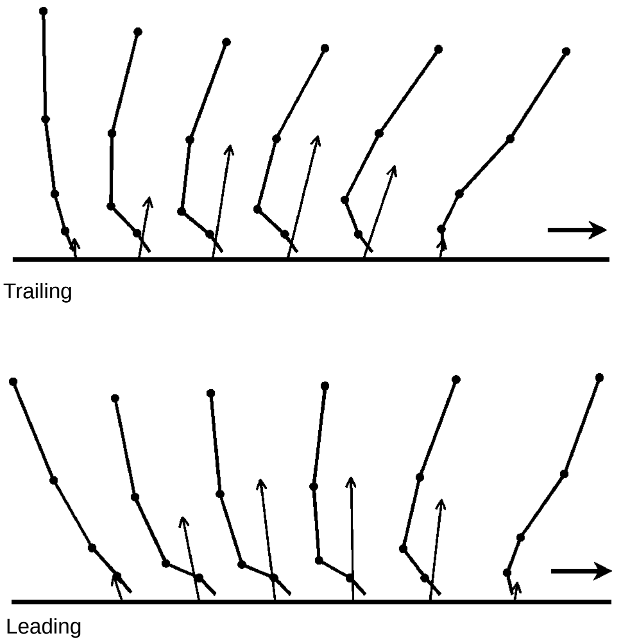

Fig 4: Stick figures of the distal parts of the trailing and leading limb during landing. Average data over all 6 horses, The thick lines represent the limb with joints (elbow, carpus, fetlock joint, coffin joint), the arrows represent the ground reaction force. The left-most figure represents touchdown, the other figures represent 20, 40, 60, 80 and 100% of the stance phase. The thick arrow indicates the movement direction of the horse.

Ground reaction force

Stance duration was 27% longer in the leading limb than in the trailing limb (218 ± 22 and 171 ± 13 ms, respectively). The vertical GRF had a similar pattern in both limbs and reached peak values of approximately 1.5 times bwt in each forelimb (Figs 2, 3). There were marked differences in the horizontal GRF between the limbs. The leading limb was braking the forward movement during the first 60% of the stance phase and propelling the body in the final 40% of the stance phase. The trailing limb was hardly braking the movement and the propulsion was much larger than the leading limb.

Joint moments

The coffin joint moment in the leading limb was positive (extending) in the first half of the stance phase and negative (flexing) in the second half of the stance phase (Fig 5). The coffin joint moment in the trailing limb was negative (flexing) during the whole stance phase. The fetlock joint moment was negative (flexing) during the whole stance phase in both limbs. The carpal joint moment was negative (flexing) during most of the stance phase in both limbs.

The peak flexor joint moments of the coffin and fetlock joints were larger in the trailing limb than in the leading limb (Table 1). The difference was 41% for the coffin joint and 26% for the fetlock joint. The peak flexor joint moment of the carpal joint did not differ significantly between the limbs. The peak extensor moment in the coffin joint of the leading limb was 0.26 ± 0.18 Nm/kg bwt.

TABLE 1: Peak flexor moments in coffin, fetlock and carpal joints of the forelimb. Mean ± s.d. over all six horses

	Peak flexor joint moment (Nm/kg bwt)		
	Coffin	Fetlock	Carpus
Landing			
Trailing	-0.62^a ± 0.11	-2.44^a ± 0.19	-2.46 ± 0.19
Leading	-0.44^a ± 0.13	-1.93^a ± 0.26	-2.40 ± 0.27
Trot (Clayton *et al*. 2000)	-0.34 ± 0.06	-1.68 ± 0.29	-1.63 ± 0.22

^{a}Denotes significant difference between limbs (P<0.05).

Discussion

In the present study, we described the joint moments during the stance phase of landing to investigate whether (1) there are only flexor moments and no extensor moments during the stance phase, (2) moments are different between leading and trailing limb and (3) moments during jump landings exceed those during trot. Joint moments were calculated using inverse dynamic methods. The accuracy of the calculated moments was influenced by several errors. Because of the small moment arm of the GRF with respect to the coffin joint, the coffin joint moment is very sensitive to errors in this moment arm. These errors can originate from inaccuracy of the point of application of the GRF, misalignment of the coordinate systems of the force plate and motion analysis system, inaccurate location of the coffin joint centre of rotation with respect to the hoof markers or noise in the measurement of the hoof markers. A cumulative error in this moment arm of 1 cm, which can be assumed to be the upper limit, results in errors in the peak flexor moment of 20–30% and in the peak extensor moment of 50%. These errors originate from measurement errors, which vary randomly among trials (point of application, noise) or horses (location of the joint centre, alignment of the coordinate systems) and partially average out when performing the statistical analysis for the entire group. Nevertheless, remaining errors might still be substantial and some care should be taken when interpreting small differences in coffin joint moments. Although the fetlock and carpal joint moments are also influenced by these errors, the resulting error is relatively small (6–8% for 1 cm) because of the higher absolute values of these moments. Another potential source of error is the differentiation of the noisy position data to obtain the segmental accelerations. However, due to the small masses of the distal segments, the inertial forces (which are calculated from the accelerations) are negligible compared to the GRF. The influence on the final accuracy is, therefore, negligible (total ignorance of the inertial forces results in errors of 1%). Similarly, differences between the actual inertial properties and the literature values determined *in vitro* are irrelevant.

The interindividual variation in joint moments was small, enabling averaging of results over all horses. Similarly small variation was also found in studies on walk and trot (Clayton *et al.* 1998; Colborne *et al.* 1998), but not in a previous study on GRFs during jumping (Schamhardt *et al.* 1993). The large variation in the study by Schamhardt *et al.* 1993 is probably due to the use of inexperienced horses. The results of the only experienced jumper in that study resemble the present results. This suggests that, with training, the interindividual variation decreases and standard movement and loading patterns are

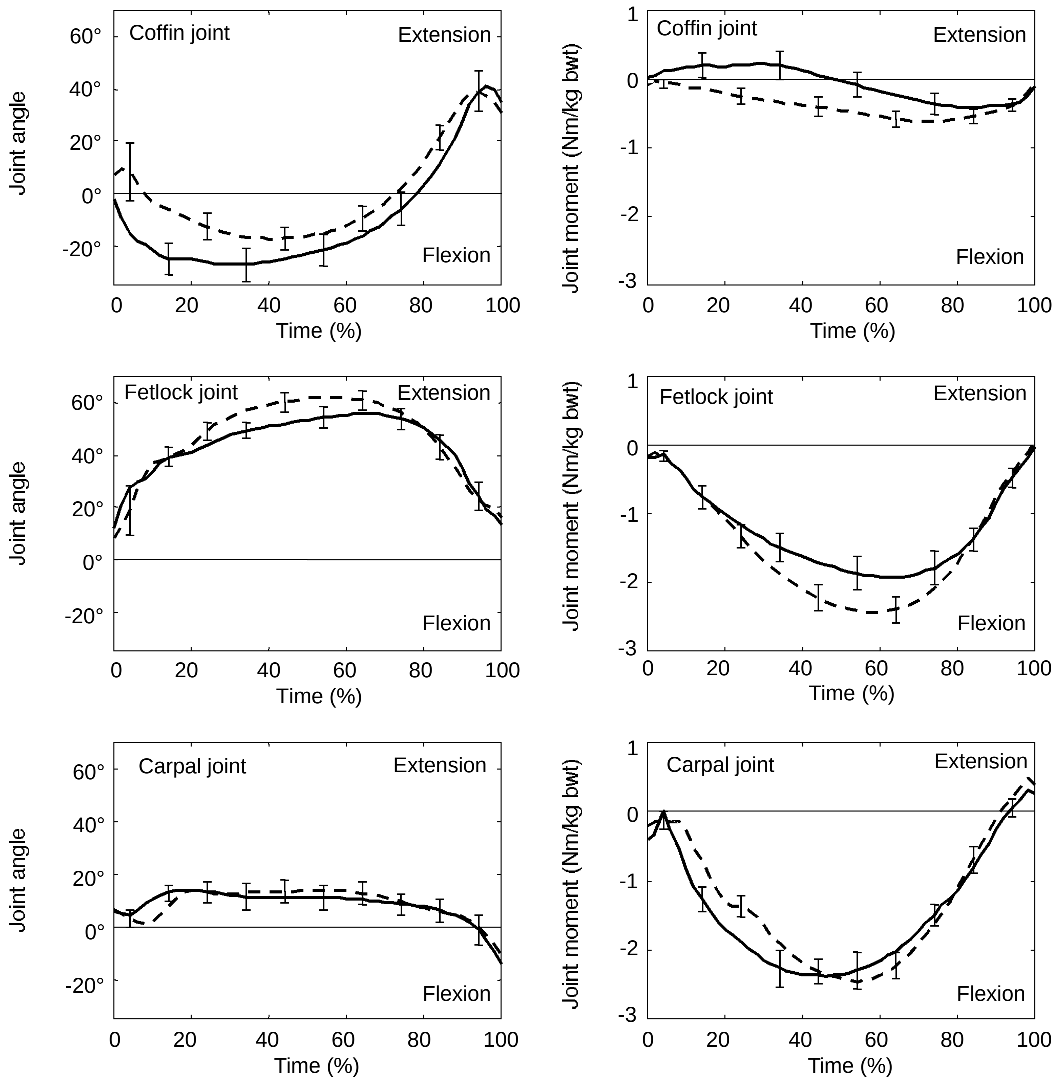

Fig 5: Joint angles and moments in the leading (solid line) and trailing (dashed line) limb during the stance phase of landing. Average values over all 6 horses, brackets represent ± 1 s.d.

acquired. This is in agreement with the low variation found during walk and trot.

During jumping, the 2 forelimbs are used differently. The leading forelimb is placed later and more forward than the trailing forelimb (Leach *et al.* 1984). This difference in limb placement is accompanied by differences in GRFs and joint moments; the horizontal GRF is negative during the first part of the stance phase of the leading limb, whereas it is positive during the whole stance phase of the trailing limb. Furthermore, there is an extensor coffin joint moment in the leading limb, which is absent in the trailing limb, and some flexor joint moments are smaller in the leading limb than in the trailing limb. The extensor coffin joint moment in the leading limb, which was not found in the trailing limb, is probably related to the forward placement of the limb. Due to this placement and the corresponding high velocity, the hoof tends to knuckle over, which has to be prevented by a positive joint moment. This moment can be generated either by the digital extensor muscles or by the extensor branches of the *tendo interosseus*. Previously, the extensor muscles were thought to extend the limb at the end of the swing phase (Jansen *et al.* 1992), whereas the extensor branches were thought to ensure a proper hoof orientation at touchdown (Jansen *et al.* 1993). The present results indicate that the extensor branches and/or muscles also have another function; they prevent knuckling over of the hoof during the first half of the stance phase in the leading limb during landing. The force required for this function is much larger than for the former functions; the peak extensor coffin joint moment during landing is 20 times as large as during the swing phase of trot (Lanovaz *et al.* 1999). This function might also be present during other activities with fast and forward limb placement. Remarkably, no extensor coffin joint moments were found during normal walk and trot (Clayton *et al.* 1998; Colborne *et al.* 1998), although the limbs are also placed forward during those gaits. The tendency to knuckle over is probably less due to the lower velocity during those gaits or due to the hard surface used in those studies, which cannot by penetrated by the toe of the hoof. The application of a heel wedge, which also increases the tendency to knuckle over, did result in an extensor coffin joint moment during trot (Clayton *et al.* 2000a).

The flexor joint moments of the coffin and fetlock joints were larger in the trailing limb than in the leading limb. Furthermore, they exceeded the reported joint moments during trot (Table 1; Clayton *et al.* 2000b). This indicates that the flexor tendons (the *tendo interosseus* and the tendons of the deep and superficial digital flexor) are loaded most in the trailing limb during landing. Repeated landings with the same lead might, therefore, result in excessive loading of the flexor tendons in this limb. Regular changes of lead will give a more even distribution of tendon loading between the right and left limbs and might limit the risk of injuries. This conclusion is based on inverse dynamic analysis and could not have been reached if the GRF only was measured. This further illustrates the introductory statement that tendon loading cannot be determined from GRF alone, but should be estimated from inverse dynamic analysis.

Inverse dynamic analysis can be used to identify activities with high tendon loading, but it cannot be used to differentiate between individual tendons. In order to understand overload-induced injuries, it is necessary to know the individual tendon loads and to compare these loads with the ultimate strength of the tendons. It should be possible to estimate tendon loads by combining inverse dynamic analysis with a model of the lower limb, which incorporates the mechanical properties of the tendons and their lines of action (Meershoek and Schamhardt 1998). However, such a model, based on *in vitro* data obtained from different horses, could introduce additional errors.

In conclusion, joint moments during landing are consistent between horses. Flexor tendon loading is larger during landing than during trot and is larger in the trailing limb than in the leading limb. Furthermore, there is an unexpected loading of the extensor tendon in the leading limb.

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Manufacturers'addresses

[1] Qualisys, Sävedalen, Sweden.
[2] Bertec Inc., Columbus, Ohio, USA.

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