Evaluation of the Tekscan F-SCAN system for measurement of the kicking force in horses

A. Fürst[1], L. D. Galuppo[2], C. E. Judy[3], J. Auer[1], J. R. Snyder[2]

[1] Equine Department of the Vetsuisse Faculty, University of Zurich, Switzerland, [2] Department of Surgical and Radiological Sciences and the [3] Veterinary Medical Teaching Hospital, School of Veterinary Medicine, University of California, Davis, USA

Summary

The incidence of fractures after a kick, coupled with marked soft tissue trauma at the site of injury, suggests that the force of a kick from the hind limb of a horse is enormous. The goal of this study was to measure this force and to investigate whether the Tekscan F-SCAN in-shoe pressure measuring system is suitable for quantification of the impact strength of a kick from a horse. The system was tested in 6 horses that had undergone clinical examination and gait analysis. The sensor-shoe combination was attached to each hind foot and the horse was stimulated to kick against a wall. The F-SCAN system measured the maximum vertical and horizontal force (N), the main contact area (cm^2) of the sole with the floor (stance phase limb) or wall (kicking limb) and the duration (sec) that the sole was in contact with the floor or wall. In addition, each kicking event was recorded with a video camera for subjective evaluation. The mean kicking force measured was lower than that recorded in horses trotting on a treadmill, where the forces exerted on one limb were similar to the horse's body weight. The results of this study indicate that the Tekscan F-SCAN system is not ideally suited to measure the force of a kick of a horse *in vivo*.

Keywords: horse, kick, force of a kick, Tekscan, sensor, equestrian injury

Evaluation des Tekscan F-Scan Systems zur Messung der Schlagkraft der Hintergliedmasse eines Pferdes

Die Häufigkeit von Frakturen und die ausgedehnten Weichteiltraumata nach Schlagverletzungen lassen vermuten, dass die bei einem Hufschlag übertragene Kraft sehr hoch sein muss. Ziel dieser Arbeit war es, diese Kraft zu messen und zu untersuchen, ob sich das Tekscan F-Scan System dazu eignet, die Schlagkraft des Pferdes zu quantifizieren. Nach vorangegangener klinischer und orthopädischer Untersuchung wurde das System an 6 Pferden getestet, indem der dazugehörige Sensor in einen Hufschuh eingebettet und das Pferd anschliessend zum Ausschlagen gegen eine Wand stimuliert wurde. Das F-Scan System berechnete bei jedem Schlag die maximale vertikale bzw. horizontale Kraft (N), die Kontaktfläche (cm^2) der Hufsohle mit dem Boden (Standbein) oder der Wand (schlagendes Bein), sowie die Kontaktdauer (sec) mit dem Boden oder der Wand. Gleichzeitig wurde jedes Ausschlagen auf Video aufgezeichnet und die Schlagkraft auch subjektiv bewertet. Die gemessenen Kräfte waren jedoch tiefer als die in einer vorangegangenen Studie, bei der Messungen an auf dem Laufband trabenden Pferden durchgeführt wurden. Dabei entsprachen die auf die Gliedmassen einwirkenden Kräfte etwa dem Gewicht des Pferdes. Die Resultate unserer Studie weisen darauf hin, dass das Tekscan F-Scan System nicht ideal zur Messung der Schlagkraft eines Pferdes *in vivo* ist.

Schlüsselwörter: Pferd, Hufschlag, Schlagkraft, Tekscan, Sensor, Pferdesportverletzung

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Introduction

Injuries caused by hoof kicks are common and can have serious consequences for horses as well as for humans (Derungs et al., 2004; Eckert et al., 2011). A retrospective study conducted at the Equine Clinic of the Vetsuisse Faculty, University of Zurich, showed that approximately 50% of horses referred because of a kick injury had a bone fracture (Derungs et al., 2004). This finding coupled with marked soft tissue trauma at the site of injury suggests that the force of a kick from a horse is enormous. Studies on the risk and consequences of kick injuries in people have shown that the mortality rate of kicked equestrians is high and that riding a horse can be more hazardous than motorcycle or car racing (Busch et al., 1986; Exadactylos et al., 2002; Eckert et al., 2011). In a study of equestrian injuries, being kicked by a horse was the second most common cause of injury after falling off a horse (Abu-Zidan and Rao, 2002). Laws mandating the use of crash helmets in equestrian events were introduced in many countries to minimise the risk of injury. To our knowledge, there have been no studies measuring the force of a kick from a horse. The goal of this study was therefore to measure this force in vivo using the Tekscan F-SCAN in-shoe pressure measuring system, which was developed for use in human kinetics (Young, 1993). This system was able to measure the force exerted by each region of the hoof while walking and trotting on a treadmill (Judy et al., 2001). Obtaining more information about the force of a kick could aid in the design of protective clothing for people. A variety of in-shoe measuring systems are available and their use and applications have been discussed (Nevill et al., 1995). We hypothesised that the Tekscan F-SCAN system is useful for measuring the force of a kick from a horse.

Animals, Material and Methods

Horses

Six horses donated to the University of California, Davis, for reasons unrelated to disorders of the hind limbs were used. The age, breed and sex of the horses varied, but all were known to kick when stimulated appropriately. The study was approved by the University of California, Davis, Institutional Animal Care and Use Committee. The signalment was recorded for each horse and a lameness examination carried out and recorded on video. Each horse was weighed, and the weight borne by the hind limbs was estimated by placing only the hind limbs on a scale while the horse was standing square on both hind feet. This weight was used to calibrate the sensors for use with the Tekscan F-SCAN measuring system. All horses were unshod.

Measurement of the force of a kick

The Tekscan F-SCAN system is an in-shoe pressure measuring system that has been used primarily for gait analysis on treadmills in human kinetics. It uses ultra-thin plastic sensors in the shape of a human foot. Each sensor contains 960 piezoelectric elements composed of quartz crystals, which generate an electric current when deformed. The amplitude of the electric current is proportional to the force applied to the sensors and can be amplified and displayed on a computer. Piezoelectric measuring systems are very sensitive over a wide range of forces and also can be used to measure the heart rate of a standing person or the impact on a dummy during

Fig. 1: Tekscan F-SCAN and the horseshoe system prepared for measuring the force of a kick.

Fig. 2: The sensor and specialized shoe are attached to the sole of the foot.

Fig. 3: The horse is placed with its hind end toward a cement wall.

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an automobile crash (McLaughlin et al., 1996; Young, 1993). Only the front part of the sensor (from the toe to the arch of the foot) was used to record the force of a kick because this region fits the sole of the hoof. Each sensor was placed between two 2-mm plastic pads, which were incorporated into a custom-made horseshoe (Fig. 1). A sensor-shoe combination was attached to each hind foot to measure the force of the kicking limb and the stance phase of the non-kicking limb (Fig. 2). The sensors were connected to a converter, which was fastened to the fetlock with Velcro. The measuring system was connected via a 10-m cable and a 16-bit receiver card to a microcomputer with the corresponding pressure and force measurement software program. To obtain meaningful measurements, the Tekscan sensors must be calibrated to the anticipated pressure range (Brimacombe et al., 2009). Therefore, before obtaining any force measurements, each sensor was individually calibrated with the previously recorded weight borne by the hind limbs with the horse standing square.

All horses were restrained using a halter and lead shank and placed with their hind end towards a cement wall. The distance between the wall and the back hooves was 40 to 50 cm, depending on the length of the hind legs of each horse, to make sure that the horse did not miss the wall when kicking. Strips of tape were placed 20 cm apart on both the floor and the wall so that the distance between the horse and the wall and the site of contact between the hoof and the wall could be determined (Fig. 3). This was achieved by recording each kicking event with a video camera. All kicks were evaluated subjectively based on the speed and severity of the kick and the noise created by the impact of the foot against the cement wall and graded on a scale from 1 (weak) to 5 (very strong).

The F-SCAN system measured the maximum vertical and horizontal force (N), the main contact area (cm^2) of the sole with the floor (stance phase limb) or wall (kicking limb) and the duration (sec) that the sole was in contact with the floor or wall. A colour code was used to indicate the force of a kick whereby the colour represented the maximum vertical force that was measured by each sensor.

Induction of kicking

At the start of each measuring trial, kicking was provoked by touching the hind limbs of the unsuspecting horse with a whip. If this failed, kicking was triggered by touching the horse on the rump and upper thigh with a sharp object attached to a stick or by stimulating the pastern using an electrode that emitted a mild electric charge of 50 mAs.

Results

The horses weighed 505 to 670 kg with a mean (± SD) of 562 ± 59 kg. The signalment, body weight and weight borne by the hind limbs, the result of the orthopaedic examination and the disposition of the horses are listed in Table 1. Two of 6 horses were mildly lame (grade 2/5); one of those horses (no. 1) had mild right hind limb lameness, possibly due to a fall in the horse trailer the day before admission. The other horse (no. 3) was slightly lame because of pododermatitis the day after the hooves were trimmed.

Induction of kicking

Kicking could not be elicited in any of the horses by touching the hind limbs with a whip. Horses nos. 1 and 3 kicked weakly when a sharp object was used. Stimulation of the pastern area using an electrode induced kicking four times in horse no. 5 and twice in horse no. 6. None of these methods elicited kicking in horse no. 4, which was then sedated with 200 mg of xylazine, administered intravenously, blindfolded, and stimulated

Table 1: Results of clinical, lameness and behavioural examinations in 6 horses used to measure the force of a kick.

Horse	Signalment	Body weight; weight borne by hind limbs (WHL)	Orthopaedic examination	Disposition
1	Thoroughbred, mare, 5 years	586 kg; WHL, 230 kg	Mild lameness in right hind limb at trot (2/5)	Nervous, unpredictable
2	Thoroughbred, gelding, 4 years	532 kg; WHL, 220 kg	Sound	Shy, slightly nervous
3	Thoroughbred, gelding, 6 years	537 kg; WHL, 220 kg	Mild lameness in left hind limb at trot (2/5)	Nervous
4	Quarter horse, gelding, 18 years	542 kg; WHL, 220 kg	Sound	Very quiet
5	Warmblood, gelding, 5 years	670 kg; WHL, 290 kg	Sound	Very quiet
6	Quarter Horse, gelding, 6 years	505 kg; WHL, 210 kg	Sound	Very quiet

again with the electrode in the pastern region. The horse reacted by kicking the floor vigorously. Horse no. 2 could not be stimulated to kick at all.

Kicking force

A total of 80 frames per second were recorded for a period of 10 seconds, which yielded a total of 800 frames for data analysis. The force curve was compared with the video footage to determine the moment of kicking. The force of a kick was then derived from the force-versus-time graph (Fig. 4). The force recorded from kicks of the left and right hind limbs ranged from 1'413 to 3'333 N (2'476 ± 717 N). The force on the weight-bearing hind limb during kicking was also measured and ranged from 325 to 7'805 N (3'041 ± 2'138 N). A total of 10 kicks could be analysed, and in 9 cases, data of both hind legs could be assessed. The results are shown in Table 2.

Discussion

The relatively high incidence of fissure fractures of the radius and tibia in horses that have been kicked by another horse shows that the force of the impact must be strong (Derungs et al., 2001). In previous studies it was estimated that a horse is able to kick with a force 1.8 times its body weight (Kriss and Kriss, 1997), which is equal to a force of up to 1'000 kg (=10 kilonewtons, kN) delivered by one hoof. Another study estimated that the force of a kick from a horse exceeded 10 kN (Firth, 1985). In a study on equine cadaver bones, the typical impact energy to fracture or fissure the radius or tibia ranged from 11 to 23 kN (Piskoty et al., 2012). However, the direction of a kick in relation to a targeted bone and the tension of that bone also affect the probability of a fracture.

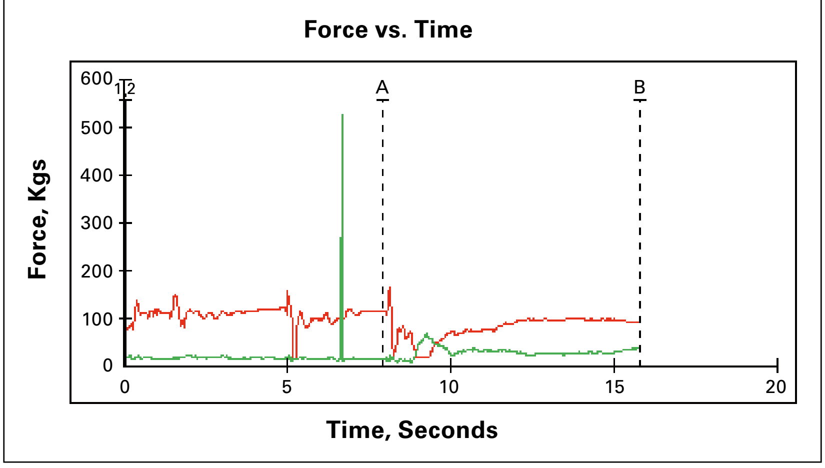

Fig. 4: Force-versus-time recording of the kicking (green) and non-kicking (red) hind limbs of a horse while kicking a wall.

The measured forces of the kicks in this study ranged from 1'413 to 3'333 N. Interestingly, during kicking, the force measured in the weight-bearing limb exceeded the force delivered by the kicking limb in 6 of 9 cases, in which forces on both hind legs could be measured. The mean kicking force was lower than that recorded in horses trotting on a treadmill (Judy et al., 2001), in which the forces exerted on one limb were similar to the horse's body weight. The reason for the lower force of a kick may be related to the measuring technique used. The sensors generated the sum of all forces acting on the limb, and this force was often higher in the weight-bearing limb because all sensors were activated simultaneously. In contrast, because the sensor plate did not extend to the weight-bearing part of the hoof wall, and in many instances the kicking hoof hit the wall at an angle, the resultant total force was lower in the kicking limb. The technique used to attach the sensors to the hoof also may have altered the measurements because of shear forces (Perino et al., 2007). Another reason for the low measured forces may have been reluctance of the horse to kick the concrete wall a second time. The major difficulty in this study was induction of a consistent kick response. Irrespective of the method used, only the first stimulus induced kicking in some of the horses. After a maximum of four attempts, the horses reacted by moving forward instead of kicking, possibly because they became accustomed to the procedure of stimulation or kicking a cement wall elicited pain.

All of the horses in the present study were unshod, and thus a comparison between shod and unshod horses with respect to the force of a kick was not possible. A study that evaluated the Tekscan F-SCAN measuring system for lameness diagnosis in horses found no difference in the forces exerted by shod and unshod hooves (Judy et al., 2001). However, one must keep in mind that these force measurements show the total force borne by the entire surface of the sole and not the force delivered by a portion of the horseshoe; the same total force acting on a smaller area increases the pressure. Likewise, the number of measurements was too small to determine the relationship between the body weight of the horse and the force of a kick. This limitation also applied to the effect of distance of the horse from the wall on the force of a kick. However, the force of a kick primarily depends on the speed of the hoof at the moment of impact and only indirectly on the distance between the horse and the wall.

The difficulty of continuous pressure measurement during an impact using the Tekscan system was described by Pain et al. (2008). The total impact peak force may be missed because of the low dynamic response time, which leads to errors and highlights the importance of sampling rate (Walker, 2014). Sumiya et al. (1998) con-

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Table 2: Measured forces generated from kicks of hind limbs and the adjacent weight bearing limb in 6 horses.

Horse	Kicking Force (N)	Force Recorded From Weight-Baring Limb (N)	Subjective Kick Score
1	RH 2966	LH 325	3/5
2	No kick induced		
3	LH 2109	RH 2933	2/5
	RH 1413	LH 1966	1/5
4	RH 1609	LH 1163	1/5
5	LH 3111	RH 7805	3/5
	RH 3333	LH 3622	3/5
	LH 2892	RH 3692	3/5
	RH 2879	LH no measurement	2/5
6	LH 2843	RH 2216	2/5
	RH 1600	LH 3643	1/5

RH: right hind limb
LH: left hind limb

cluded that the dynamic response time of the F-Scan Tekscan System was too low for accurate dynamic measurements. It is therefore likely that the video frequency of 80 frames/second was not sufficient to capture the actual peak force of a kick. Based on a muscular contraction time of 20 to 40 ms and the high speed of a kick, a frequency of 1'000 frames/second would be more likely to capture the peak force. Furthermore, the accuracy of the Tekscan System may be lower than reported in dynamic loading situations because of the effects of shear loads, loading between curved surfaces or small contact areas. Sensor output and output variability depend on the stiffness of the contact materials (Brimacombe et al., 2009). Lou et al. (1998) found the sensor to be sensitive to surface conditions, loading speeds and temperature, and rated the F-Scan Tekscan sensor system unsuitable for hard surface contact. In addition, the F-Scan in-shoe pressure measuring system was reported to be extremely sensitive to calibration (Perino et al., 2007). It seems therefore that in-shoe pressure measuring systems are inferior to force plates for measuring absolute impact forces (Lange et al, 2012). Nevertheless, preliminary studies done at the Veterinary Medical Teaching Hospital, University of California, Davis, showed that the F-SCAN system was able to withstand forces of up to 10'000 N without physical or functional damage and was therefore chosen for these in-vivo experiments. However, the force of a kick from a horse depends on many factors and is difficult to predict in a real situation. Therefore, laboratory data on the minimum force required to fracture a human bone, rather than the force of a kick, should be used for developing personal protective equipment.

Conclusion

The results of this study showed that the Tekscan F-SCAN system is not ideally suited for measuring the force of a kick from a horse in an in-vivo setup. The measuring frequency (sampling rate) of the sensors was too low to reliably capture the peak force of a kick. It is possible that a vertically mounted force plate could be substituted for the in-shoe measuring system for the evaluation of the force of a kick from a horse.

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Evaluation du système F-Scan Tekscan pour la mesure de la force de frappe des postérieurs d'un cheval

La fréquence des fractures et les importants dégâts aux tissus mous consécutifs à des coups de pieds laissent à penser que la force de frappe transmise à cette occasion doit être très importante. Le but du présent travail était de mesurer cette force et de voir si le système F-Scan Tekscan est adapté pour quantifier la force de frappe d'un cheval. Après un examen clinique et orthopédique, le système a été utilisé sur 6 chevaux, en incluant le senseur dans une hipposandale et en stimulant ensuite le cheval pour qu'il rue contre une paroi. Le système F-Scan a mesuré lors de chaque coup de pied la force maximale verticale respectivement horizontale (N), la surface de contact (cm²) de la sole avec le sol (membre à l'appui) ou avec la paroi (membre donnant le coup) ainsi que la durée de contact avec le sol respectivement avec la paroi. Chaque coup de pied a simultanément été enregistré sur vidéo et le force du coup a été estimée subjectivement. Les forces mesurées étaient toutefois plus faibles que celles enregistrées chez des chevaux au trot sur un tapis roulant dans une étude précédente. Les forces exercées sur les membres étaient globalement égales au poids du cheval. Les résultats de notre étude laissent à penser que le système F-Scan Tekscan n'est pas idéal pour mesurer la force de frappe d'un cheval.

Valutazione del sistema F-Scan di Tekscan per misurare la potenza d'impulso degli arti posteriori di un cavallo

L'incidenza delle fratture e degli estesi traumi dei tessuti molli dovuti a lesioni da impatto fanno sospettare che la forza trasferita dallo scalpitio dello zoccolo debba essere molto elevata. Lo scopo di questo studio era quello di misurare questa forza e di indagare se il sistema F-Scan di Tekscan fosse idoneo a quantificare la potenza di impulso del cavallo. Dopo un esame clinico e ortopedico eseguito in precedenza, il sistema è stato testato su 6 cavalli nei quali è stato incorporato il relativo sensore nella scarpa e sono stati stimolati a scalpitare contro una parete. Il sistema F-Scan ha calcolato ad ogni colpo, la forza verticale e orizzontale massima (N), la zona di contatto (cm²) dello zoccolo con il suolo (arto posteriore) o la parete (arto scalpitante), e il tempo di contatto (secondi) contro il suolo o la parete. Allo stesso tempo, lo scalpitio è stato videoregistrato ed è stata valutata soggettivamente la potenza impiegata. Le forze misurate, tuttavia, erano inferiori a quelle di uno studio precedente le cui misure erano state raccolte su un tapis roulant per cavalli. Le forze che agiscono sugli arti sono approssimativamente equivalenti al peso del cavallo. I risultati del nostro studio indicano che il sistema F-Scan di Tekscan non è idoneo a misurare la potenza d'impulso di un cavallo.

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Corresponding author

Prof. Dr. med. vet. Anton Fürst
Equine Department,Vetsuisse Faculty, University of Zurich
Winterthurerstrasse 260, 8057 Zurich, Switzerland
Phone: +41 44 6358473
E-Mail: afuerst@vetclinics.uzh.ch