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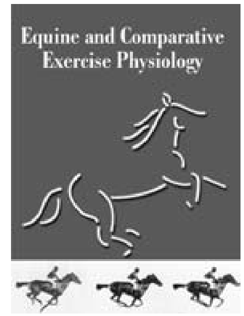

Determination of coefficient of friction between the equine foot and different ground surfaces: an *in vitro* study

Nicolas J Vos[1] and Dirk J Riemersma[2]
[1]University of Prince Edward Island, Atlantic Veterinary College, 550 University Avenue, Prince Edward Island CIA 4P3, Canada
[2]Traberpark 'Den Heyberg', B299 Kevelaer, Germany

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Abstract

Slippery surfaces are a continuous concern in equine veterinary practice during both treatment and orthopaedic work-ups, especially when horses have to trot on circles[1,2]. Sliding of the equine foot on the ground with the potential of injury is prevented if the horizontally acting accelerating or decelerating forces on the foot do not exceed maximal friction. Friction can be calculated and therefore anticipated if the coefficient of friction (μ) between the foot of the horse and the particular ground surface is known. Friction between shod and unshod cadaver equine hooves and different ground surfaces (concrete, tarmac and rubber) was determined by pulling the hooves horizontally in a uniform motion. Horizontal forces (F_h) were measured on a force plate and with a portable digital electronic force meter. The coefficient of friction (μ) was calculated as the quotient between F_h and the gravity force (N) of the object[3], hence: $\mu = F_h/\text{N}$. This study has shown that the coefficient of friction between equine hooves and a specific ground surface can be determined using a portable digital force meter or a force plate. Friction significantly depended not only on the type of surface but also on shoeing of the equine foot. Bare feet showed more friction with the hard surfaces (bricks and tarmac), the shod feet showing more friction with the rubber surfaces. Coefficients of friction could be used to estimate the possibility of injuries occurring in the equine industry during exercise and/or lameness or pre-purchase examinations.

Keywords: friction; feet; equine; ground; surface

Introduction

The hoof–ground interaction, known as ground reaction force (GRF), has been found to be a major determinant in studies relating track properties to limb physiology and possible pathology, both in horses, cattle and humans[4,7–12]. Hard ground surfaces are associated with a high incidence of accidents and/or lameness in both man and horses[12–14]. In equine veterinary practice, hard surfaces, such as concrete and tarmac, are used for lameness evaluation or pre-purchase examination and rubber surfaces are used during high-speed treadmill exercises[15,16]. An optimum for the quality of the hard ground surface for the aforementioned exercises remains to be determined.

The horizontal component of the GRF (F_h) may cause sliding of the foot if the frictional forces are exceeded. Frictional forces (f) are defined as the product of the coefficient of friction (μ) and the vertical component of the GRF (normal force, N)[3], hence: $f = \mu N$. Note that the formula does not contain an area factor. Friction is independent of the contact area involved. Friction results from Coulomb forces between two surfaces where the coefficient of friction μ is a *constant* for the interaction between two known materials (here, ground and foot characteristics). Friction is differentiated into static friction and a somewhat lower kinetic friction. Static friction (f_s) is defined as the maximal frictional force which resists the onset of motion of an object if a horizontal force (F_h) is applied to the object. Kinetic friction (f_k) is the frictional force which is measured during motion of an object[3]. If an object is in uniform motion, the pulling force (F_h) required to keep this motion going equals the kinetic frictional force (f_k). Relevant for the interaction between an equine foot and a specific ground surface is at first the maximal static friction. The horizontal forces F_h should not exceed maximal static friction, to prevent the horse from sliding. Once sliding occurs it will be the kinetic friction that should prevent the acceleration of the body, resulting in a possible accident. Once the coefficients of static (μ_s) and kinetic (μ_k) friction between two surfaces have been determined, the measurement or calculation of the normal force (N) suffices to calculate maximal friction and therefore determines the maximum tolerable horizontal force preventing the horse from sliding and the potential of injury.

Two pulling test protocols were performed. In the first pulling test protocol, a *portable force meter device* was used. The portable force transducer or meter is an electronic load cell and can be used to perform tests in outdoor situations. The magnitude of the pulling forces was read from a display and could not be recorded electronically in our set-up. The second protocol included a *force plate.* The force plate consists of a series of sensing measuring elements supporting the four corners of a loading plate. When a horse or a foot steps on a force plate, the position and three-dimensional magnitude of the force is measured by deflection of the sensing (piezoelectric) elements within the plate. The displacement of the sensing elements is proportional to the force applied to the plate and creates an electrical signal that is amplified, recorded, converted and stored on an electronic medium[17].

The objective of this *in vitro* study was to determine the coefficients of static friction μ_s and kinetic friction μ_k between equine feet and different ground surfaces. Although in theory it might suffice to pull pieces of horn or steel (shoe) over the surfaces, we have chosen a more realistic set-up. This was accomplished by pulling shod and unshod equine feet over concrete, pavement, tarmac and rubber surfaces while measuring the pulling forces. The forces required to produce onset of motion reflected static friction and the forces required to maintain uniform motion reflected kinetic friction. The forces were measured by means of a portable digital force meter and a force plate.

Materials and methods

The 26 feet used in this study were obtained from fore- and hind limbs of horses that had no known history of foot disorders. Thirteen feet were shod with normal steel shoes, 13 feet were bare. Three feet were recently shod, the others showed wearing from normal use. The specimens were tested within 24 h after death; the horses and ponies were not killed for this study. The cadaver limbs were disarticulated at the level of the distal interphalangeal joint. The feet were cleaned and their weights were measured. The horn quality of the hoof was subjectively (poor, middle and good) documented. A small metal hook was screwed into the horn in the middle of the dorsal hoof wall, and connected with a chain to the pulling device.

Since it was intended to apply uniform motion, pulling devices were used rather than pulling the objects by hand. The pulling devices (Fig. 1) consisted of a battery-driven toy motor vehicle (Cart, Pull Motor Inc., Taiwan), on which the unster was mounted (unster protocol), pulling the digit forward with uniform velocity. In the force plate protocol, a larger electromotor (Harvard respirator pump, Bodine Electric Company, USA) was used to pull the equine digits with uniform velocity. Care was taken to test the specimens on a horizontal plane in a horizontal direction. The distances between the specimen and the testing device were standardized. The feet were placed on the clean and dry surfaces and pulled horizontally in different directions on the same surface. The specimens were pulled over a distance of 10 cm[18] in a straight line with the pulling time documented as well. One pull over each one of the surfaces was documented as one run. All forces were expressed in Newton.

In the first pulling test protocol, a *portable digital force measuring device* (Ametek Accu Force 2, Mansfield & Green DIV, USA) was used with an accuracy of $\pm 0.5\%$ full-scale deflection of the rated capacity and a pulling range of 0–200 N. The portable force meter device was calibrated before measuring (Netherlands Calibration Organization/International Standards Organisation certified). In the portable force meter protocol, 26 cadaver feet were studied as they were pulled over seven different hard surfaces and two soft surfaces, in different directions but always in a horizontal plane. The portable force meter protocol included 40 runs per cadaver digit per ground surface. The magnitude of force was read from the display at the onset of movement (static friction), and three times during uniform motion (kinetic friction). The recorded magnitude of force was mathematically averaged to represent the mean force to require onset of motion (F_{hs}) and the mean force required to maintain motion (F_{hk}).

Seven hard ground surfaces, frequently used in veterinary practices for walking and trotting horses, were included in this first pulling test (Fig. 2). The common hard ground surfaces tested were: small concrete bricks (SCB) ($10.5 \times 10.5 \times 8$ cm, semi-concrete pavement bricks), large concrete bricks (LCB) ($21 \times 10.5 \times 6$ cm, semi-concrete pavement bricks), rough tarmac (stone mastic asphalt (SMA)) and smooth tarmac (dense asphalt concrete (DAC)). The less commonly used surfaces were: a bare, concrete-coated smooth floor (BC), pavement slabs (PS)

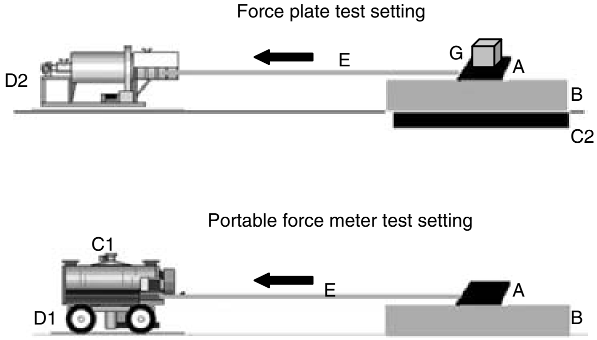

Fig. 1 The force plate test setting (top) and the portable force meter test setting (bottom). The horizontal pulling force was measured with a portable force meter (C1) and a force plate (C2). The equine foot (A) was placed on a hard ground surface (B), and connected with a metal chain (E) to a pulling system, cart (D1) or pump (D2), pulling the digit horizontally in uniform motion. In the top set-up, the digit was loaded with an extra lead weight (G)

(30 × 30 × 6 cm concrete pavement tiles) and a hardened sandstone brick street (HS) (21 × 14 × 6 cm aurora cobblestone). Two relatively soft surfaces were also tested: smooth rubber (SR) and rough rubber (RR) (30 × 30 × 2 cm rubber tiles).

The second pulling test protocol included a *force plate* (Kistler model 9261, dimensions 600 × 900 mm, Kistler Instrumente AG, Winterthur, Switzerland), with Kistler 9865B charge amplifiers (Charnwood Dynamics Limited, Rothley, Leicestershire, UK). The force plate was embedded in a concrete pathway to measure the vertical and the two horizontal (longitudinal and transverse) components of the GRF with a sampling frequency of 2500 Hz. The force plate was covered by four different hard surfaces (SCB, LCB, SMA and DAC) and calibrated for the weight of the material. The surfaces were kept in position during the experiments by their own weight and the friction with the plate. The force plate protocol included, 20 cadaver feet with ten pulling exercises per cadaver digit in three different horizontal directions, per ground surface. The analogue data generated by the force plate were digitalized and stored on an electronic medium for later analyses. To improve the accuracy of the force plate recordings, the cadaver digits were loaded with an extra 10.5 kg of lead weight, in order to generate a larger signal, reducing the errors of measurement while recording. The pulling forces required for the onset of motion (F_{hs}) and the pulling forces during uniform motion (F_{hk}) were recorded consecutively during each run.

After conclusion of the pulling tests, small sagittal pieces of the hoof wall were cut from the different feet, weighed and dried for 2 weeks in a drying oven and weighed again in order to establish the hydration percentage of the hoof wall during testing.

Coefficients of static friction (μ_s) and kinetic friction (μ_k) were calculated for every combination of shod and unshod hooves on the hard- and soft-ground surfaces tested in this study. The μ was calculated by dividing the horizontal pulling force F_h by the normal force N (the total weight of the objects (foot plus weight) times 9.81 N).

The magnitude of the first peak of the F_{hs} (static friction) and the mean F_{hk} (kinetic friction) were compared for the 26 feet and seven different hard

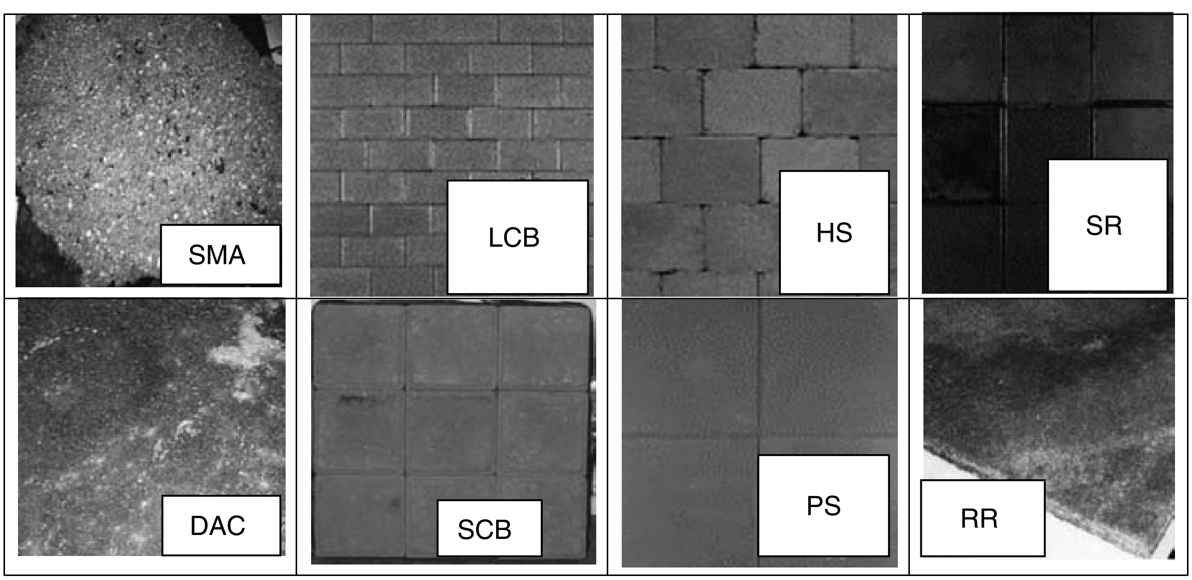

Fig. 2 Seven hard ground surfaces, frequently used in veterinary practices for walking and trotting horses, were included in this study. The common hard ground surfaces tested were: small concrete bricks (SCB), large concrete bricks (LCB), rough tarmac (SMA) and smooth tarmac (DAC). The less commonly used surfaces were, pavement slabs (PS) and a hardened sandstone brick street (HS). Two relatively soft surfaces were also tested: smooth rubber (SR) and rough rubber (RR)

ground surfaces and two soft surfaces within the portable force meter protocol using a one-way analysis of variance (ANOVA), with the individual feet as the in-between factor and the ground surfaces as the within factor. To evaluate differences in measurements between the portable force meter and the force plate and the hydration percentage of the feet, Student's *t*-tests were applied.

The magnitude of the first peak of the F_{hs} (static friction) and the mean value of F_{hk} (kinetic friction) were compared for the 20 feet and four different ground surfaces within the force plate protocol using a one-way ANOVA, with the individual feet as the in-between factor and the ground surfaces as the within factor. Statistical analyses were performed with *SPSS*, version 12.0 (SPSS, Chicago, IL). Significance level was set at $P < 0.05$.

Results

The mean weight of the unshod cadaver feet was 0.89 kg (range 0.64–1.14 kg). The mean weight of the cadaver feet shod with a shoe was 1.72 kg (range 1.14–2.42 kg).

Table 1 shows the static (F_{hs}) and kinetic pulling force (F_{hk}) between bare feet and different ground surfaces as measured in the portable force meter protocol. Table 2 shows the same for feet shod with a steel shoe. Both tables include the calculated static (μ_s) and kinetic friction coefficients (μ_k). The static (F_{hs}) and kinetic pulling force (F_{hk}) between bare feet and different ground surfaces and shod feet with different ground surfaces measured in the force plate protocol are listed in Tables 3 and 4, respectively.

The pulling distance of the feet was 10 cm. From the pulling time recorded, it was calculated that the feet were pulled with a velocity of $0.02\,m\,s^{-1}$, generated in *c.* 2 s. The average acceleration would therefore be *c.* $0.01\,m\,s^{-2}$. This figure is low, which is important, since accelerating forces are superimposing F_{hs}.

Within the portable force meter pulling testing, unshod cadaver feet pulled over the small concrete bricks street (SCB), showed significantly more friction in comparison with feet that were bare and pulled over a smooth tarmac (DAC), bare concrete floor (BC), concrete slab surface (PS) and sandstone brick surface (HS) ($P = 0.04$, 0.01, 0.04 and 0.03, respectively).

Shod equine feet showed significantly more friction on both rubber surfaces in comparison with any other hard ground surfaces. The levels of significance for differences in friction between shod feet on RR compared with shod feet on BC, PS, SMA, DAC, LCB and SCB were $P = 0.004$, 0.03, 0.003, 0.004, 0.04 and 0.04, respectively.

There was no (statistically) significant difference between unshod or shod feet pulled over SCB surfaces in comparison with the LCB surfaces.

The force plate measurements were, on average, $0.46\,N$ (range $0.01–1.0\,N\,kg^{-1}$ equine hoof) higher F_{hs} than the portable force meter measurements. Using the force plate measurements, the bare cadaver feet pulled over the small concrete brick street (SCB), showed significantly more friction in comparison with feet that were unshod or shod and pulled over smooth tarmac (DAC) ($P = 0.03$ and 0.008, respectively). There was no significant difference in F_h between bare or shod feet pulled over SCB surfaces in comparison with the LCB and SMA surfaces.

The friction between the unshod feet on the SCB, in comparison with any other hard surface with shod feet, was significantly higher. The levels of significance for differences in friction between unshod feet on SCB compared with shod feet on SMA and DAC, LCB and SCB were $P = 0.02$, 0.001, 0.02 and 0.03, respectively.

The fragments that were cut out of the ten different cadaver feet were weighed before and after they had been kept in a drying oven for 2 weeks. The difference in weight would represent the water content at the

Table 1 Pulling forces (static friction (F_{hs}) and kinetic friction (F_{hk})) measured between an unshod equine digit and different ground surfaces, in a portable force meter protocol

Portable force meter protocol, unshod equine feet	Kinetic pulling force (F_{hk}) in $N\,kg^{-1}$ with (±) standard deviation	Static pulling force (F_{hs}) in $N\,kg^{-1}$ with (±) standard deviation	Difference kinetic force (ΔF_{hk}) force plate *versus* portable force meter ($N\,kg^{-1}$)	Kinetic friction coefficient (μ_k)	Static friction coefficient (μ_s)
Ground surfaces					
Smooth rubber tile (SR)	7.34 ± 1.63	7.87 ± 0.78	–	0.75	0.80
Rough rubber tile (RR)	8.82 ± 1.62	9.63 ± 1.34	–	0.90	0.97
Bare concrete floor (BC)	5.68 ± 1.86	6.74 ± 0.31	–	0.58	0.69
Concrete pavement slab (PS)	6.83 ± 0.04	6.85 ± 0.07	–	0.70	0.71
Rough tarmac (SMA)	8.11 ± 0.32	8.73 ± 1.50	ΔF_{LK} 0.86	0.81	0.86
Smooth tarmac (DAC)	7.55 ± 1.68	8.01 ± 1.41	ΔF_{LK} 0.58	0.76	0.80
Cobblestone (HS)	6.45 ± 0.10	6.5 ± 0.71	–	0.66	0.67
Large concrete bricks (LCB)	8.15 ± 0.62	8.46 ± 0.45	ΔF_{LK} 0.31	0.83	0.87
Small concrete bricks (SCB)	8.18 ± 1.30	8.83 ± 1.40	ΔF_{LK} 1.00	0.83	0.89

The table includes the calculated kinetic and static friction coefficients (μ_k and μ_s).

Table 2 Pulling forces (static friction (F_{hs}) and kinetic friction (F_{hk})) measured between shod equine digits and different ground surfaces, in a portable force meter protocol

Portable force meter protocol, shod equine feet	Kinetic pulling force (F_{hk}) in $N\text{kg}^{-1}$ with (±) standard deviation	Static pulling force (F_{hs}) in $N\text{kg}^{-1}$	Difference kinetic force (ΔF_{hk}) force plate *versus* portable force meter $N\text{kg}^{-1}$	Kinetic friction coefficient (μ_k)	Static friction coefficient (μ_s)
Ground surfaces					
Smooth rubber tile (SR)	6.69 ± 0.49	6.83 ± 0.51	–	0.67	0.68
Rough rubber tile (RR)	6.81 ± 0.15	6.84 ± 0.07	–	0.68	0.69
Bare concrete floor (BC)	3.86 ± 0.51	4.19 ± 0.48	–	0.39	0.42
Concrete pavement slab (PS)	4.67 ± 0.36	4.7 ± 0.31	–	0.47	0.48
Rough tarmac (SMA)	4.56 ± 0.62	4.67 ± 0.61	ΔF_{LK} 0.73	0.45	0.47
Smooth tarmac (DAC)	4.19 ± 0.72	4.37 ± 0.31	ΔF_{LK} 0.22	0.42	0.44
Cobblestone (HS)	3.75 ± 1.39	4.19 ± 0.89	–	0.38	0.42
Large concrete bricks (LCB)	5.31 ± 0.60	5.61 ± 0.67	ΔF_{LK} 0.01	0.53	0.56
Small concrete bricks (SCB)	5.44 ± 0.70	5.8 ± 0.81	ΔF_{LK} 0.08	0.55	0.58

The table includes the calculated kinetic friction coefficients (μ_k).

Table 3 Pulling forces (static friction (F_{hs}) and kinetic friction (F_{hk})) measured between unshod equine digits and different ground surfaces, in a force plate protocol

Force plate protocol, unshod equine feet	Kinetic force (F_{hk}) in $N\text{kg}^{-1}$ with (±) standard deviation	Static pulling force (F_{hs}) in $N\text{kg}^{-1}$	Kinetic friction coefficient (μ_k)	Static friction coefficient (μ_s)
Ground surfaces				
Rough tarmac (SMA)	8.97 ± 0.31	12.11 ± 0.02	0.91	1.21
Smooth tarmac (DAC)	8.13 ± 0.09	8.84 ± 0.07	0.82	0.89
Large concrete bricks (LCB)	8.46 ± 0.38	12.15 ± 0.31	0.86	1.22
Small concrete bricks (SCB)	9.23 ± 0.47	9.73 ± 1.00	0.94	0.98

The table includes the calculated kinetic friction coefficients (μ_k).

time of the experiments. No statistical difference was found concerning the water content of the different feet.

Discussion

Several techniques have been used to document the kinematics and kinetics of the hoof in relation to ground interaction[19–23]. Kinetic hoof and gait analysis (the temporal and the geometric characteristics of motion) can be accurately performed with the use of a force plate in a laboratory setting[24–26]. The validity and reliability of a portable force meter in determining the coefficient of friction in human research have been proved[27,28], but the use of a portable force meter in determining the coefficient of friction between an equine hoof and several ground surfaces is unique.

The coefficients of friction have been successfully used and are essential in *in vivo* research models, determining the probability of slipping of a person on dry, wet and contaminated hard ground surfaces and therefore preventing accidents from happening[6,29–31]. To the knowledge of the authors, these models are not yet used in the equine industry, but similar *in vivo* studies could provide valuable information in equine slipping accident prevention.

In this *in vitro* study, both the static and the kinetic friction were determined. The static friction was defined as the force required to produce the onset of motion of an equine foot. The forces at the onset of motion are not only required to overcome static friction, but also to accelerate the object. Since it can be quite difficult to establish accelerations in practice

Table 4 Pulling forces (static friction (F_{hs}) and kinetic friction (F_{hk})) measured between shod equine digits and different ground surfaces, in a force plate protocol

Force plate protocol, shod equine feet	Kinetic force (F_{hs}) in $N\text{kg}^{-1}$ with (±) standard deviation	Static pulling force (F_{hk}) in $N\text{kg}^{-1}$	Kinetic friction coefficient (μ_k)	Static friction coefficient (μ_s)
Ground surfaces				
Rough tarmac (SMA)	5.29 ± 0.21	8.09 ± 1,03	0.54	0.80
Smooth tarmac (DAC)	4.41 ± 0.53	5.79 ± 0.23	0.45	0.58
Large concrete bricks (LCB)	5.32 ± 0,13	6.48 ± 0.78	0.54	0.65
Small concrete bricks (SCB)	5.52 ± 0.54	5.92 ± 0.16	0.56	0.60

The table includes the calculated kinetic friction coefficients (μ_k).

without the use of a force plate, it may prove extremely difficult to establish the correct value of maximal static friction. Even if the acceleration may be low, the forces could be significant if the mass of the accelerating body is large ($F = ma$). This may explain the higher values for F_{hs} in the force plate experiments where an extra weight was applied. The first data of a run, representing static friction, were always higher in both protocols (Tables 1–4), which reflects the general principle that static friction is higher than kinetic friction[3]. The portable force meter in this study was not equipped with electronic recording of the F_h data, which could therefore only be determined four times in one run: one at the onset of motion and three during uniform motion. Within a run in the force plate protocol, the F_h data could be recorded at a considerably higher rate: over 500 data for F_h during one run. This explains why the determination of the static friction is less reliable than that of the kinetic friction in both experiments, and why the frictional forces in the force plate experiments can be more accurately determined.

Accelerating forces are zero at uniform motion and therefore were not superimposing the pulling forces F_{hk} for kinetic friction. The determination of kinetic friction is therefore less complicated and consequently more reliable. In practice, the kinetic friction would also be the most important one to be determined for safety reasons, since it is unlikely that kinetic friction can prevent an accident once the maximal static friction has been exceeded by horizontal forces. Establishing the coefficient of kinetic friction (μ_k) would therefore be the best guideline for safety limits. This could be done using a portable force meter. Though less reliable than a force plate, a portable force meter is an easy to handle, small device and more practical to use outside a laboratory setting, such as in veterinary practice.

The rough surfaces (SMA, LCB and SCB) resulted in fluctuating magnitudes of F_h in the force plate recordings. These fluctuations were more apparent when bare feet were pulled over the hard ground surfaces. It was possible to identify whether a specific foot was not smoothly sliding from one brick to the next or was caught by a pebble partially embedded in the rough tarmac, causing obstruction, rather than through friction. These 'pebble obstructions' have been reported in friction tests between cow digits and floors with 2.5 mm aggregate (pebbles) embedded in concrete, resulting a significant increase in resistance to sliding[11].

This study showed that significant differences in friction may arise from different shoeing and different ground surfaces. While bare feet show higher friction with the hard surfaces (bricks and tarmac), the shod feet showed more friction with the rubber surfaces.

Hoof wall hydration might influence the mechanical properties of equine hoof keratin, the principal component of the hoof wall[5,32,33] and therefore might influence friction properties of bare feet. Our cadaver limbs therefore were quickly processed after they had been taken from the euthanazed animal. The hydration of the cadaver feet was measured, but a significant contribution to the results in this study has not been found.

The documentation of friction or friction coefficient determination concerning equine feet and different hard ground surfaces has not been reported before in the literature. The numbers of sliding accidents within veterinary practices are not available in the literature either. Therefore, little is known about safety within veterinary practices where lameness evaluations are performed. However, measurements of friction performed by automobile and traffic safety organizations are performed on a yearly basis in order to increase road safety. Traffic safety rules in the Netherlands recommend an asphalt road friction coefficient of at least 0.45, preferably 0.54[34]. A road with a friction coefficient <0.40 is considered to be unsafe[3,34]. With the exception of the HS and BC surfaces, all the friction coefficients between equine feet and the surfaces observed in this study are within the Dutch guidelines of safe hard ground surfaces for automobiles. The optimum coefficient of friction for cattle and pig floors has been reported to be between 0.4 and 0.5 for cows and pigs walking in a straight line[11,35]. The way in which friction may change once sliding occurs (i.e. by wearing of the surfaces and temperature rise), may be different for a car tyre and an equine foot[3], but equine and bovine or porcine feet are certainly comparable. No rules or regulations are documented for hard ground surfaces used for equine lameness evaluations in veterinary practice. Taking into account the fact that slipping does not always result in injury, prior experience with a slippery, hard ground surface results in proactive adjustments to safely traverse the slippery surface in both man and cows[36,37]. Subsequently, previous slipping experiences of the horse might change its (ab)normal gait, and could therefore influence the lameness work-up considerably. The need for a hard ground surface with a very high coefficient of friction, such as rubber, might not be necessary, since people with an orthopaedic problem did not demonstrate greater friction requirements then adults without a disability[31]. Based upon the aforementioned studies and the results of this study, the minimal coefficient of friction between an equine foot and a hard ground surface should be ± 0.45. Dry, clean and levelled roads consisting of rough tarmac and/or large/small bricks, according to this study, show a coefficient of friction high enough to prevent horses with shod or unshod feet from sliding[1,2].

The friction coefficients determined in this study can be put to use in future investigations into evaluating the safety of lameness work-up on hard ground surfaces and lunging rings in veterinary practices. During lunging, the friction between the discontinuously loaded feet of the horse and the ground surface has to deal with the centrifugal force $F_c = mv^2/R$, with (R) being the radius of the circle and (v) the velocity of the horse with mass (m). The radius of the lunging circle and/or the speed of the horse should be adjusted to the maximal friction available between the horse's feet and the ground surface.

The portable force meter could be used as part of an *in vitro* study to determine the coefficient of friction of any racetrack in order to both objectively relate track properties to (past) injuries and prevent (future) sliding injuries from happening. The force plate protocol could very well be used in *in vivo*-as well as further *in vitro*-research in coefficient of friction determination between equine feet and other hard ground surfaces. The techniques presented here can be used to establish guidelines for maximal friction of different types of shoeing, as well as guidelines for friction of surfaces used in equine veterinary practices or other environments in the equine industry.

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