The Veterinary Journal 227 (2017) 49–57

Contents lists available at ScienceDirect

The Veterinary Journal

journal homepage: www.elsevier.com/locate/tvjl

Original Article

Comparing subjective and objective evaluation of show jumping competition and warm-up arena surfaces

E. Hernlund[a,*], A. Egenvall[b], S.J. Hobbs[c], M.L. Peterson[d], A.J. Northrop[e], A. Bergh[a], J.H. Martin[f], L. Roepstorff[a]

[a] Swedish University of Agricultural Sciences, Department of Anatomy, Physiology and Biochemistry, Box 7011, 750 07 Uppsala, Sweden
[b] Swedish University of Agricultural Sciences, Department of Clinical Sciences, Box 7054, 750 07 Uppsala, Sweden
[c] University of Central Lancashire, Centre for Applied Sport and Exercise Sciences, Darwin Building 201, Preston PR1 2HE, UK
[d] University of Maine, Mechanical Engineering Department, 5711 Boardman Hall, Orono, ME 04469-5711, USA
[e] Anglia Ruskin University, Department of Life Sciences, East Road, Cambridge CB1 1PT, UK
[f] Myerscough College, Department of Agriculture and Countryside, Preston PR3 0RY, UK

ARTICLE INFO

Article history:
Accepted 7 September 2017

Keywords:
Biomechanical surface test
Equestrian arena
Functional surface properties
Show jumping
Subjective assessment

ABSTRACT

The development of safety and quality standards for equestrian surfaces needs to be based on objective, repeatable measurements which allow comparisons between surfaces. These measurements should incorporate the assessment of surface performance by riders. This study provides data from objective and subjective assessment of functional properties of high-level show jumping competition and warm-up arenas. Twenty-five arenas in nine international show jumping events were evaluated by mechanical in-situ testing with a surface tester, rider assessments using visual analogue scales (198 riders provided 749 arena evaluations), descriptions of arena constructions and by laboratory tests of surface material. Mixed models were used to present subjective evaluation of rider perception of the functional properties for each arena while controlling for rider and event. The association between objective and subjective assessments were also explored creating mixed models, controlling for rider and event.

Mechanical measurements of impact firmness, and to a lesser extent cushioning and grip, had a significant positive association with the riders' perception. Responsiveness as assessed by the Orono biomechanical surface tester (OBST) was negatively associated with the riders' perceptions, which suggests riders and the OBST had different concepts of this functional property and that further developments of the OBST might be necessary. Objectively measured uniformity showed no useful association with riders' perception. Even though arena assessments were made by top level riders, a substantial inter-rider variation was demonstrated.

Introduction

Sport surfaces impact the performance of both human and equine athletes (Peterson et al., 2010; Binnie et al., 2014) as well as the incidence of injuries (Murray et al., 2010; Egenvall et al., 2013; Balazs et al., 2015). In particular competition surfaces must provide safety during maximal loading while ensuring optimal performance.

The international governing body for equestrian sports, the Fédération Équestre International (FEI) seeks to develop safety and quality standards for equestrian sport surfaces, however there is a lack of objective evidence available to guide this process. Key components required for evaluation of surfaces include: in-situ functional testing of the surface by objective test methods, laboratory tests of materials, systematic evaluations by riders, on-horse measurements of the horse-surface interaction, understanding of the construction and maintenance, and epidemiological data related to injuries associated with surfaces. This paper incorporates elements of the first three components.

Measurements using horses are crucial for understanding of the loading patterns that horses apply to the surfaces and how they vary. Studying horse-surface interaction reveals stresses experienced by the limb which offer the possibility to explore the aetiology of injuries to the locomotor system (Crevier-Denoix et al., 2015). However, standardized mechanical equipment offers more consistent comparisons between surfaces. The granular surfaces used in equestrian sports are sensitive to peak load and loading rate (Li et al., 2009; Guisasola et al., 2010). The mechanical tests should therefore ideally mimic critical performance conditions for

* Corresponding author.
E-mail address: Elin.Hernlund@slu.se (E. Hernlund).

http://dx.doi.org/10.1016/j.tvjl.2017.09.001

the athlete, but are not expected to be able to directly predict external or internal forces acting on them (Nigg, 1990). Test equipment developed for human sports has limited value because of the lower loads and loading rates (Kruse et al., 2013), which underestimates the effect of the deeper layers of the surface. Recent test methods developed for equine sports surfaces have been designed with the intention of replicating critical portions of the horse's loading of the surface (Peterson et al., 2008; Setterbo et al., 2011). The complexity involved in the occurrence of injuries suggests that no given single measurement value from these simplified mechanical models of horse-surface impact and loading can be said to directly influence specific injuries. But knowing, for example, the peak load on a surface, helps to quantify demands on soft and hard tissues. Ultimately, the relevance of these mechanical measurements needs to be investigated by correlation with horse injury data.

Laboratory tests of surface material are limited in their ability to capture the full demands of the horse on the surface.[1] However, they are a critical component in understanding the factors affecting a particular in-situ testing outcome. Factors influencing arena performance include: sand shape, mineralogy, particle size and size distribution, moisture content, fibre components composition and wax content (Barrey et al., 1991; Orlande et al., 2012; Bridge et al., 2014).

Objective measurements of how well surfaces allow for sufficient athletic performance need to be guided by experienced riders. Riders could evaluate how the horses respond to the surface with regards to, for example, energy return and grip. In human sport surface research, Aldahir and McElroy (2014) stressed the importance of correlating data for playing quality with players' perceptions of the surface through questionnaires and surveys with a large number of responses. Elucidation of the association between athlete perception of surface performance and the surface's mechanical properties could help improve the performance related relevance of objective mechanical tests. A prerequisite for this approach is understandable terminology defining the most important functional description of the surfaces along with objective, quantifiable measurements of comparable properties.

The aim of this study was to compare subjective and objective evaluation of show jumping competition and warm-up arena surfaces. By investigating how the measurements from a test machine related to top riders' assessments, we aimed to evaluate whether the objective surface test is relevant to participants in the show jumping sport.

Materials and methods

Arenas

Competition ($n = 9$) and warm-up ($n = 16$) arenas (total $n = 25$) in seven international show jumping events with the highest category of prize money (known as CSI5*, according to the FEI competition ranking system) and two events with the second highest category (CSI4*) in six European countries were included in the study. The events were chosen based on the expected chance of getting the same riders participating in several events and geographical accessibility for moving the test equipment.

Surface material samples and laboratory tests

A material sample of approximately 1 kg was taken from the top layer of the sand based arenas. Particle size distribution was determined by sieving and sedimentation according to ISO 11277:2009(E).[2] Water content was determined by drying samples at 45 °C to a constant mass based on a modified standard ASTM D2216.[3] The percentage of organic content was determined by burning off the organic materials from an oven dried sample in a furnace at 440 °C according to ASTM D2974.[4] When applicable, the wax content was determined using Soxhlet extraction (Bardet and Sanchez, 2011).

Defining sport related and measurable arena properties

With the goal of defining standard terminology to describe equestrian sport surfaces, communication had been initiated with the International Jumping Riders Club in 2008. During a hearing with international riders and sports stakeholders, terminology describing arena properties was documented and explanations of the terms were evaluated from a biomechanical perspective. Six terms describing the essential functional surface properties were selected on the basis of being familiar to the riders and also possible to measure mechanically. The terms were published in by the international sanctioning body in the Equine Surfaces White Paper by Hobbs et al.[1]

Subjective evaluation of arena properties

Respondents

All available riders on the starting list for the selected competitions, who gave their consent to participate in the study, evaluated the arenas at the event through a questionnaire.

Questionnaire

One questionnaire per event and rider was used to evaluate properties and overall scores for each arena by using visual analogue scales (VA-scales). For expanded method see Appendix: Supplementary material. Verbal anchors of contrasting adjectives were presented at the end-points of each scale to aid the rider in the rating of each property. The functional properties and adjectives were: Impact firmness — ranging from soft to hard, cushioning — ranging from deep to compacted, responsiveness — ranging from dead to active, grip — ranging from slippery to high grip, uniformity — ranging from variable to uniform, consistency over time — ranging from no change to changeable, overall rating — ranging from bad to good. The VA-scale was scored on a 101-point scale (0–100) and transformed to a 0–5-rating with the resolution unchanged.

Objective evaluation of arena properties

The Orono biomechanical surface tester (OBST)

The OBST is a 2-axis instrumented mass-spring-damper impact device initially designed for testing Thoroughbred racetracks (Peterson et al., 2008). The device interacts with the surface in both vertical and horizontal directions. A metal hoof connected to a heavier mass, guided by angled rails, is dropped on to the surface (see Appendix: Supplementary material). As the hoof impacts the ground the falling mass above transfers additional load onto the hoof by a shorter vertical axis compressing the spring and damper, at the same time allowing a forward slide of the hoof. The intent of the design is to be commensurate to the impact and loading phase of the support phases of the gait described by a number of authors (Johnston and Back, 2006; Thomason and Peterson, 2008; Robin et al., 2009; Setterbo et al., 2009; Crevier-Denoix et al., 2010, 2013a,b, 2015; Parkes and Witte, 2015). The device is modified to better fit equestrian sports as described in Tranquille et al. (2015). Nine channels of data were acquired using sensors including a string potentiometer, a single axis load cell, a tri-axial accelerometer, a tri-axial load cell, and a linear potentiometer (for sensor specification see Tranquille et al., 2015). Data from each impact was recorded with 16-bit resolution at 5000 Hz using a custom written MatLab data acquisition and analysis script (The Math Works). All arenas were tested by repeated drops over the surface at a spatial resolution of approximately 15 m between drop sites. The arenas were prepared with a maintenance tool combining superficial harrowing and rolling before being tested with the OBST.

Parameter description and signal processing

Sensor outputs from the OBST were used to objectively measure the functional properties. Each measurement was chosen based on its appropriateness to define the biomechanics of the property. Impact firmness was characterized by the peak

[1] See: the Equine Surfaces White Paper: http://www.fei.org/system/files/EquineSurfacesWhitePaper.pdf (accessed 28 August 2017).

[2] See: ISO 11277:2009(E), Soil quality – Determination of particle size distribution in mineral soil material – Method by sieving and sedimentation. www.iso.org (accessed 28 August 2017).

[3] See: ASTM D2216-10, Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass, ASTM International, West Conshohocken, PA, 2010. www.astm.org (accessed 28 August 2017).

[4] See: ASTM D2974-14, Standard test methods for moisture, ash, and organic matter of peat and other organic soils, ASTM International, West Conshohocken, PA, 2014, www.astm.org (accessed 28 August 2017).

vertical deceleration of the metal hoof at impact, which represents the shock experienced by the horse at hoof impact (Thomason and Peterson, 2008; Chateau et al., 2009). Cushioning was determined using the peak vertical force from the tri-axial load cell, as cushioning describes how much the surface absorbs and reduces peak force (Hobbs et al., 2014[1]). Grip was represented by the amount of forward slide of the metal hoof on the surface during loading. Responsiveness relates to the deformation and elastic recovery of the surface (Hobbs et al., 2014[1]) and was measured as a quotient of the compression and recoil time of the spring, mass, damper system. Uniformity, representing the spatial variation over the arena, was calculated by taking the ensemble mean of the coefficients of variation (CV), defined as standard deviation/mean, for each functional property; impact firmness, cushioning, grip and responsiveness of that arena. Consistency was not objectively measured since repeated measurements of the arenas over several days could not be performed in most events. For detailed descriptions of signal processing, parameter calculations and graphical representation of the signals in the time domain (see Appendix: Supplementary material).

Statistical methods

Descriptive statistics were used to describe the five objectively measured functional properties per arena.

Seven mixed models were created in SAS to investigate differences between arenas in subjectively rated functional properties controlling for rider and rider within event. The outcome variables were each of the six evaluated functional properties and the overall rating. Arena identifier was entered as fixed effect. Three of the outcome variables were transformed to achieve a distribution close to normality.

Modelling of association between objective and subjective arena evaluation

Associations between objective and subjective arena functional properties were explored by creating mixed models where the objective measurement was used as explanatory variable (fixed effect) and the outcome was the corresponding subjective variable. Random effects were rider and rider within event. The distributions of the outcome variables were checked for normality. Since machine measurements were spatially and independently repeated over the arenas, the mean value per arena was used to compare to the riders' evaluations. To investigate the effect of the within arena variation in the objective measurements arena-level standard deviations were entered as explanatory variables (excluding uniformity being a measurement of arena variation). Linearity between objective and subjective variables was evaluated by entering the square of the objective variables in the models. To control for collinearity during this process, the explanatory variables were centred around their median. Models were successively reduced by removing explanatory variables with the highest type III sum square P-values, until only those with P-values < 0.05 remained.

Results

Riders and response rate

The total number of unique riders at the competitions was 287; 198 responded to the questionnaire. In all events, 547 questionnaires could potentially have been completed. We received 313, giving a response rate of 57%. In total, 749 arena evaluations (up to three arenas could be evaluated on one questionnaire) were received from the riders who responded, of which 80 had one or more missing values.

Arena descriptions and material tests

Tables 1 and 2 summarize arena attributes and material analysis results. Two thirds (68%) of the arenas studied were temporary, with a sand fibre top layer on top of concrete or tarmac. The mean age of the six permanent arenas was 4 years (range, 0.5–10 years).

Objective measurements of arena characteristics

Descriptive statistics for objective measurements per arena are presented in Fig. 1. The mean number of measured drop sites for all variables per arena was 8.5. Data loss due to mechanical sensor disturbance was a problem when measuring responsiveness on some arenas, leading to total loss of the measurement on four arenas (arena ID 9, 10, 11 and 22) and additionally, an inability to calculate standard deviation on three others (4, 6 and 21).

Subjective evaluation of arena characteristics

Figs. 2 and 3 show results from subjective evaluation of arena functional properties by descriptive statistics and model output, respectively. In the mixed models, 669 arena evaluations from 174 riders were included. Rider, entered as a random effect, explained on average 22% of the variation in the observed values

Table 1
Arena attributes, construction and water content; information on arena construction and design was provided by the arena producers or local event organisers.

Arena ID	Event ID	Out/In	C/W	P/T	Top layer type	Base	Top layer depth (cm)
1	A	Out	C	P	Sand + fibre	Ebb and flow, gravel	22–23
2	A	Out	W	P	Sand	Gravel	18–22
3	A	Out	W	P	Sand	Gravel	18–22
4	B	Out	C	P	Turf	Aggregates	TURF
5	B	Out	W	P	Natural turf	Soil	
6	B	Out	W	P	Natural turf	Soil	
7	C	In	W	T	Sand + fibre	Concrete	18–20
8	C	In	C	T	Sand + fibre	Concrete (old brige)	18–20
9	D	Out	C	T	Sand + fibre	Tarmac	22–25
10	D	Out	W	T	Sand + fibre	Tarmac	18–22
11	D	In	W	T	Sand + fibre	Tarmac	18–22
12	E	In	W	T	Sand + fibre	Concrete	15–17
13	E	In	W	T	Sand + fibre	Concrete	15–17
14	E	In	C	T	Sand + fibre	Concrete	15–17
15	F	In	C	T	Sand + fibre with waxed sand below	Concrete	8 + 15
16	F	In	W	T	Sand + fibre	Concrete	16–18
17	F	In	W	T	Waxed sand + fibre	Concrete	16–18
18	G	In	W	T	Sand + fibre	Concrete	15–17
19	G	In	C	T	Sand + fibre	Concrete	15–17
20	G	In	W	T	Sand + fibre	Concrete	15–17
21	H	In	C	T	Sand + fibre	Rubber mat on concrete	16–18
22	H	In	W	T	Sand + fibre	Rubber mat on concrete	16–18
23	I	In	W	T	Sand + fibre	Rubber mat on concrete	8
24	I	In	W	T	Sand + fibre	Rubber mat on concrete	8
25	I	In	C	T	Sand + fibre	Rubber mat on concrete	8

ID, identification; Out, outdoor arena; In, indoor arena; C, competition; W, warm-up; P, permanent; T, temporary.

Table 2
Arena material composition.[a]

Arena ID	Event ID	Particle size distribution (mm) in percentage of solid particle dry weight								Organic content, weight %	Fibre weight %	Water content %
		Clay/clay-sized <0.002	Fine silt 0.002–0.006	Silt 0.006–0.02	Coarse silt 0.02–0.06	Fine sand 0.06–0.2	Sand 0.2–0.6	Coarse sand 0.6–2	Gravel 2.0–20			
1	A	0.5	0.0	0.7	4.3	30.8	58.9	4.8	0.0	0.1	1.2	19
2	A	1.2	0.3	1.5	12.4	70.3	13.5	0.5	0.2	0.4	0.0	17
3	A											14
4	B	Turf								Turf	Turf	Turf
5	B											
6	B											
7	C	1.1	0.0	0.5	1.2	74.9	21.6	0.4	0.3	0.2	2.5	13
8	C											15
9	D	Missing								Missing	Missing	Missing
10	D											
11	D											
12	E	0.8	0.4	1.5	18.2	75.3	2.7	0.6	0.5	0.3	4.7	23
13	E											20
14	E											27
15	F	1.9				25.7	67.8	4.6	0.0	3.4	4.3	21
16	F	1.2	0.3	0.8	6.4	81.1	8.9	1.3	0.0	0.6	5.1	25
17	F	1.9				48.0	49.0	1.0	0.0	1.0	4.0	17
18	G	0.5	0.2	0.5	2.0	94.8	0.8	0.4	0.7	0.2	2.5	22
19	G											26
20	G											25
21	H	1.9	0.2	0.8	4.1	90.0	2.8	0.2	0.0	0.4	7.1	25
22	H											26
23	I	3	3.2	3.7	11.9	68.4	9.3	0.4	0.1	0.5	4.1	23
24	I											24
25	I											27

[a] The sieve sizes used for particle separation can be seen in the table. Sieve sizes differed slightly between the waxed and un-waxed sample analysis and sedimentation was not performed on the waxed sand samples. As such, no information is provided on the size distribution for fine particles for the waxed sand samples. Wax content was 1.2 and 1.4% in the material samples from arenas 15 and 17, respectively. From three arenas (9, 10 and 11) no material sample was collected (data reported as missing). If several arenas were composed of the same material only one sample was sent for analysis.

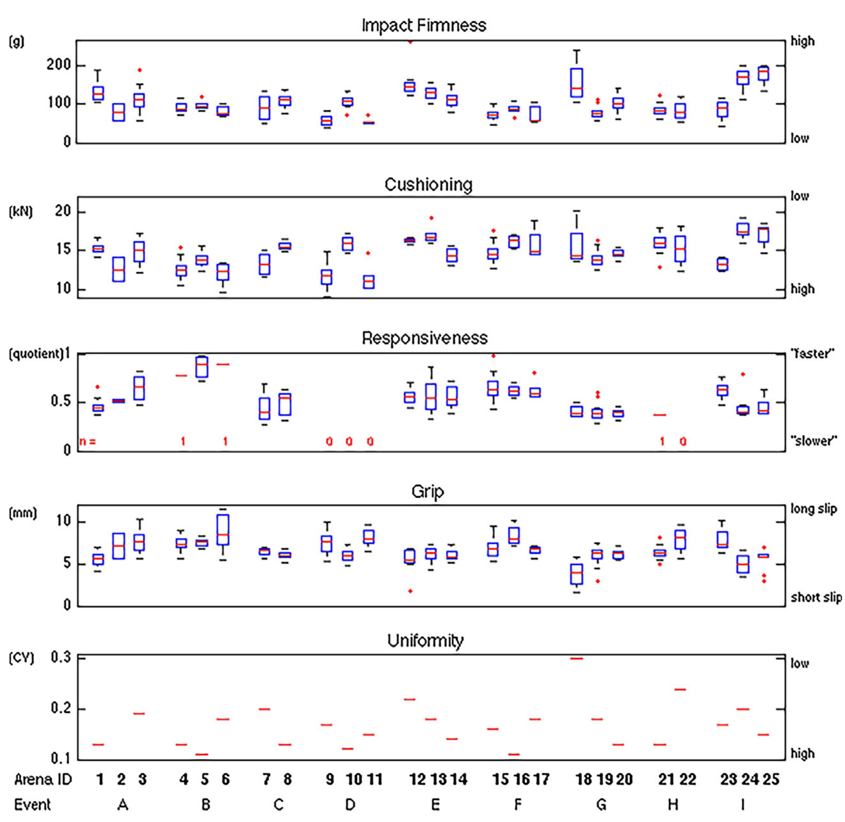

Fig. 1. Objectively measured functional characteristics per arena presented using standard box and whiskers plots. Uniformity has only one value per arena, the arena mean of the coefficients of variation (CV) represented by the red horizontal line. Arena and event identification (ID) are the same as in Table 1. The number of valid measurements (n) per arena is noted in the bottom row. For responsiveness, n is also presented within the subplot to display number of measurements remaining after data loss.

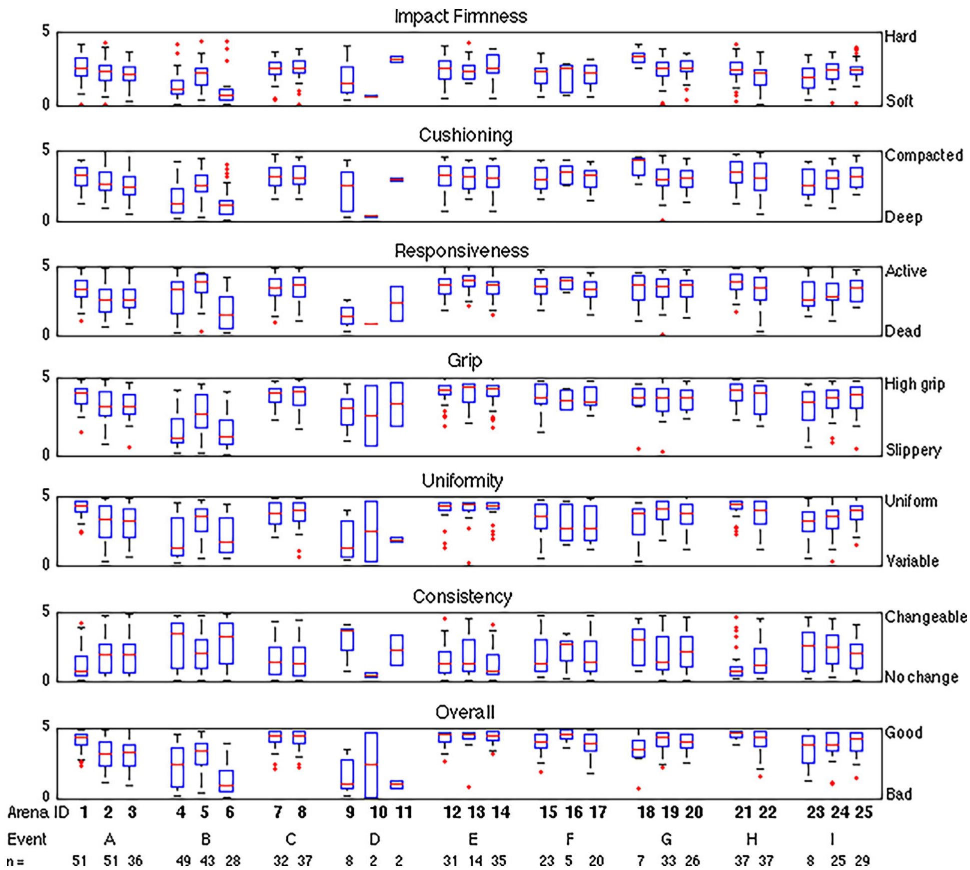

Fig. 2. Descriptive statistics of subjective evaluation of arenas presented using standard box and whiskers plots. Arena identification (ID) numbers and events are according to Tables 1 and 2. The number of evaluations (n) per arena is noted in the bottom row.

according to the variance component estimate (ranging from 6% for cushioning to 31% for grip).

Association between objective and subjective assessment

Fig. 4 presents the association between the objectively measured and the subjectively assessed functional properties. For responsiveness, standard deviations were not included (because of data loss). In all other models when entered as fixed effects, standard deviations were non-significant and therefore omitted. For all functional properties, the objective variable showed a statistically significantly association with the corresponding subjective variable ($P < 0.05$). Table 3 summarizes model outputs.

Discussion

This study presents the evaluation of functional properties of equestrian surfaces using both subjective and objective methods. Comparisons of the two methods indicate that the biomechanically based objective tests show some useful associations with experienced riders' subjective assessments (Fig. 4). Additionally, the study provides basic information on arena design and material characteristics of CSI4* and CSI5* show jumping arena surfaces (Tables 1 and 2).

There is an obvious challenge to comparing two test methods without access to an existing reference standard. These riders' subjective assessments of the surfaces' functional properties are important in order to guide surface measurements related to performance. The riders that participated in this study were at the top level of the sport with the best possible experience of riding many horses on different footings and were selected as the best-suited evaluators of surface performance and good representatives of the competitor population at this level. Athlete assessment of sport surfaces has previously been performed using visual analogue scales (Andersson et al., 2008; Starbuck et al., 2016). This form of athlete-guided assessment is undoubtedly more difficult in show jumping compared to sports where only human athletes participate. In show jumping, the rider does normally not interact directly with the surface except for the inspection of the course before the ride. This means that the interpretation of the surface response made by the rider is perceived with the horse's body as a mediator. This poses additional challenges to the rider's subjective assessment, especially since the horse has leg mechanisms with efficient spring-like behaviour (Minetti et al., 1999) and damping capacities (Gustås et al., 2001; Wilson et al., 2001). Also, since horses have higher body mass than humans, the human's interaction with the ground may not be able to reach the lower surface layers. As such, walking on an arena surface will likely not give the required information, but may actually give false information. In this study, the riders evaluated all arenas from one event on the same VA-scales, which may have produced clustering in these observations. This was controlled for in the statistical analysis by entering 'rider within event' as a random effect. Statistical modelling of the data revealed that the riders contributed up to 31% of the variation. We believe this emphasises the benefits of using standardised equipment for surface assessment. The substantial between-rider variation in surface assessment also highlights the challenge to comparing mechanical tests to subjective surface assessments when effectively there is no

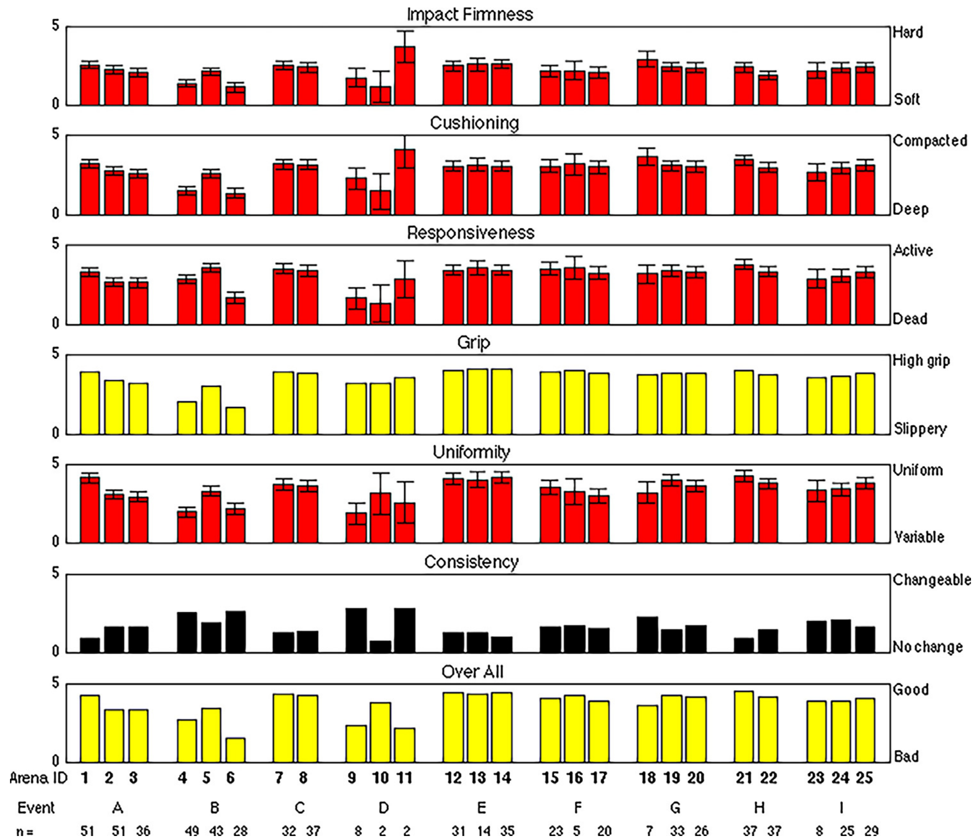

Fig. 3. Subjective evaluation per arena from mixed model output (controlling for rider and rider within event) presented as least square means with 95% confidence intervals (CI) given by error bars. For grip, uniformity and overall scores no CI is presented since these variables were transformed to achieve normality (no relevant SE obtained after back-transformation). Red bars represent variables deemed normally distributed; the yellow were best transformed by square and the black coloured variable by square root.

reference standard. It also emphasises the need for the inclusion of many questionnaire responses and adequate statistical modelling in this process.

The standardised biomechanical surface tester (OBST) used in this study impacted the surface in a way intended to represent a simplified version of the primary and secondary impacts of the loading phase, while replicating peak loads from the descent of the centre of mass of the horse during support (Peterson et al., 2012[5]). Modifications to the OBST from the original design developed by Peterson et al. (2008) were made with consideration of the demands on the horse during show jumping at Grand Prix level. The design changes (see Appendix: Supplementary material) have attempted to take into account a maximal loading situation, although scientific data to guide this process are still limited to smaller jumping efforts at slower speeds. Load-time graphs from jumping horses presented by Schamhardt et al. (1993) and Crevier-Denoix et al. (2013a, 2015) reveal similar patterns with rapidly increasing vertical load during the primary hoof-surface impact followed by a secondary load increase as the weight of the horse is transferred onto the limb. In the Appendix: Supplementary material we have compiled relevant biomechanical data describing decelerations, loads and loadings rates in hoof-ground interaction to allow the reader to put the OBST settings and parameters into context. From this data, it is evident that the loading rate (kN/s) of the OBST is higher than the available in vivo data, both measured as peak loading rate and as an average rate from the first touch of the hoof to the peak load during full support. Also, the peak load (kN) reached by the OBST is often higher than the examples seen in the published load time graphs from horses jumping lower fences. In the experiment by Schamhardt et al. (1993), one horse jumped a vertical fence of 1.3 m on a force plate covered with a rubber mat. This produced a load on the trailing fore limb at landing of twice the bodyweight, giving an approximate peak load of 14.4 kN. In the study by Crevier-Denoix et al. (2015), the peak vertical load was approximately 7–8 kN for a 524 kg horse jumping a 1 m high × 1.9 long hurdle on hybrid and natural turf. Estimates from duty factor (Witte et al., 2006) suggest that (even without jumping) at submaximal gallop speed peak forces may reach 2.5 times the bodyweight. At impact of the OBST, the metal hoof contacts the surface and spring compression and surface deformation of the cushion occur. The sliding mass then pushes the metal hoof vertically and horizontally into the surface, which results in maximum compression of the spring and peak force production. The force is damped during secondary loading throughout by the damper attached to the rigid metal limb structure. Mimicking the entire force time curve produced by the horse would require a more complex mechanical limb design to provide a longer contact time and progressive limb loading up to a maximum. Test devices that are simplistic in their simulation of player loading but provide repeatable and easily interpretable measurements in mechanical testing of surfaces are often used for human sports (Dixon et al., 2015). The Artificial Berlin Athlete is usually considered the best practical solution for measuring the shock absorbing properties of sports surfaces by the IAAF (Durá et al., 1999). While this device also has a shorter contact time than athletes performing critical movements, the equipment is still used to differentiate between different surfaces for a number of sports. It is widely acknowledged that more biofidelic testing is

[5] See: the Racing Surfaces White Paper: http://www.racingsurfaces.org/white-papers/white_paper_1_20120508.pdf (accessed 28 August 2017)

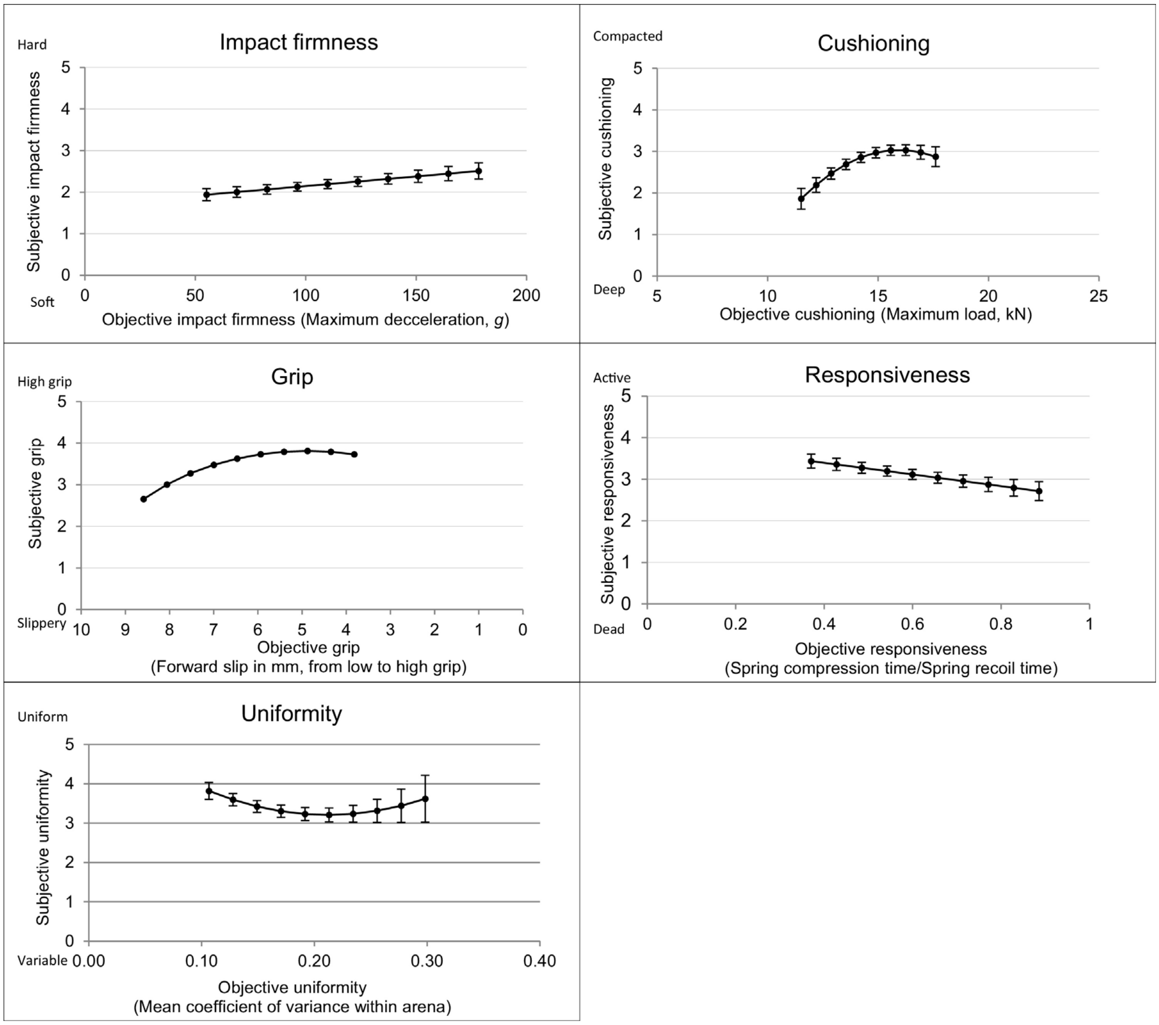

Fig. 4. The association between each subjectively perceived functional property (on a 0–5 scale) and the corresponding objectively (by the Orono biomechanical surface tester) measured property (controlling for rider and rider within event). In each graph the subjective parameter is predicted as a function of the objective explanatory variables using the ESTIMATE function in SAS. The smallest and the largest arena means for each objective parameter together with eight uniformly distributed values between these were used to estimate subjective scores according to the mixed models. A confidence interval (CI) of 95% is presented for each estimate. This was not possible in the grip model due to transformation of the outcome variable.

needed in order to elucidate the surfaces' full role in sporting performance and injury risk. For example, advances in equipment to measure more relevant high rates of dynamic loading in more than one direction simultaneously are being requested in human sports (Dixon et al., 2015). In addition, for both equine and human sports there is a scientific gap concerning 'in competition' biomechanical data on athlete-surface interaction that are needed to inform the further development of mechanical tests.

For impact firmness, cushioning and grip, there was a positive association (from smaller to larger) between the subjective and objective assessments. For impact firmness, the model was linear (Fig. 4). Higher decelerations measured by the OBST were perceived as harder by the riders. The effect was relatively small, which could be due to smaller differences in impact firmness found between elite level competition surfaces. Additionally, the damping capacity of the horse's hoof and limb (Gustås et al., 2001;

Table 3
Model output from mixed models where association between objective and subjective functional properties were explored (controlling for rider and rider within event).

Property for model outcome	Transformation of outcome variable (subjective)	Explanatory variables (from OBST) in final model	Estimate (effect of objective variables on subjective variable)	Standard error	P
Impact firmness	None	Impact firmness	0.005	0.001	<0.001
Cushioning	None	Cushioning	0.147	0.023	<0.001
		Cushioning^2	−0.060	0.013	<0.001
Grip	Square	Grip	−1.67	0.209	<0.001
		Grip^2	−0.545	0.144	0.001
Responsiveness	None	Responsiveness	−1.40	0.309	<0.001
Uniformity	None	Uniformity	−6.80	1.42	<0.001
		Uniformity^2	55.0	19.8	0.006

Wilson et al., 2001) may limit the magnitude and frequency content of impact shock transmitted back to the rider.

For cushioning and grip the squared objective parameters were significant and the associations were curvilinear. Regarding the quality of this association, it should be kept in mind that, in spite of the large number of riders, only a small number of surfaces were considered, and clustering within riders occurred. While all of these effects were taken into consideration with the statistical analysis, the resulting models had low power. Extensive analysis of the limited data set was emphasized to provide a reasonable external validity in the setting of high-level show jumping. Linearity vs. the outcomes (transformed) was examined and deviations from linearity were taken account of in the models. The within-arena variation of the OBST measurements was added to the models, as rider's ratings were not coupled with a specific OBST measurement (i.e. the OBST tested the arena at 'specific locations' — but riders were not asked to specifically judge these testing spots). However, the curvilinear relationship for cushioning was clearly statistically significant ($P < 0.001$), but it is possible that type I error might have occurred. When the turf venue was omitted from the dataset, the association became plain linear (data not shown). Therefore, we believe that the curvilinear shape of the associations for cushioning and grip indicate that the interpretation of the effect sizes is complex and should be performed with caution. Further exploration of the effect sizes and the linear shape of the associations and verification of the results should be performed on arenas that display more variation in functional properties.

For responsiveness, the negative association between the objective and subjective variable suggests that for these specific surfaces, the optimum energy return to the horse is provided by the surfaces with a relatively slower response time in relation to deformation time. As Ratzlaff et al. (1997) suggested, the surface response is only useful if it occurs after peak force production as the limb is unloading. This could mean that the natural frequencies of these surfaces are at the higher end of what is the optimum for the horse. The loss of data for this variable necessitates a somewhat cautious interpretation of the results. The magnitude of the elastic response from the surface might also influence the responsiveness and not only the timing, which was our focus. The objective measurement of this elastic response should be further developed. The energy return from the surface to the horse is challenging to approximate using a simplified mechanical test, given the complexity and variation of the interaction between the horse and the surface. Continued rider evaluation of surfaces and further comparisons to objective tests would help this process.

The lack of an interpretable association of subjective to objective uniformity might be explained by limitations in our study design. We expected that the magnitude of non-uniformity would be low in arenas used in these high-level events. The well-developed damping capacity of the horses' limbs (Gustås et al., 2001; Wilson et al., 2001) may also limit the sensation of non-uniformity transmitted to the rider and therefore limit the ability of the rider to perceive the properties of the surface. The spatial resolution of the OBST may also have been too low to properly assess uniformity. The objective measurement (the ensemble mean of the CV) also might not explain the subjective perceptions of riders well because some properties might have more influence on perceived uniformity. Finally, the contribution of variation in responsiveness is lacking from some arenas.

The arenas included in this study were not randomly selected, but are considered representative of arenas at the CSI4* and 5* level. Most of the arenas were constructed with a sand-fibre top-layer above a rigid base (concrete; Table 1). The measurement of impact firmness is closely aligned with the amount of cushioning (Fig. 1), which might be accentuated by the design of the arenas in this study, given that minimal cushioning is provided from deeper structures. Many riders and surface constructors state that competition arenas at this level often provide too little cushioning in relation to what they think is optimal for use in training, but that the construction enables performance in competition due to minimal energy loss. One major development potential for equestrian surfaces is to find a construction material that minimises energy loss but still provides cushioning enough to ensure safety of the horse. The use of objective measurements is critical to this process.

Conclusions

This study demonstrated that objective surface assessments using the OBST, measuring the functional surface properties of impact firmness, and to a lesser extent, cushioning and grip, were significantly and positively associated with riders' assessments of the same properties. Riders, even at the top level, displayed substantial variation when assessing the same surfaces. Hence, standardized comparisons of equestrian surfaces based on objective measurements are key to harmonising between-arena comparison. These measurements should incorporate riders' perceptions of surface performance to gain legitimacy from within the sport. Given the wide variation of rider opinions recorded in this study, this will continue to be a challenging task. Measurements from the OBST provided no absolute statements about safety of the surface. However, these data do provide comparisons between surfaces that can be linked to performance, as assessed by the riders. Continued studies should incorporate horse injury data with mechanical measurements and surface performance assessments to assist in the development of objective standards.

Conflict of interest statement

None of the authors of this paper have a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of the paper.

Acknowledgements

We would like to acknowledge the Swedish-Norwegian Foundation for Equine Research and la Fédération Equestre Internationale (FEI) for providing financial support for the study. We express our sincere thanks to all riders participating in the study. We also thank Dr. Stéphane Montavon for helping with translation of the questionnaires and Isabelle Fredricson, Carolyne Tranquille, Linda Klein, Muriel Sacks and Alexandra Blaser for assisting with data collection at the events. Preliminary results were presented orally at the FEI sports forum in Lausanne, Switzerland 28–29 April in 2014.

Appendix: Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tvjl.2017.09.001.

References

Aldahir, P.C.F., McElroy, J.S., 2014. A review of sports turf research techniques related to playability and safety standards. Agronomy Journal 106, 1297–1308.

Andersson, H., Ekblom, B., Krustrup, P., 2008. Elite football on artificial turf versus natural grass: movement patterns, technical standards, and player impressions. Journal of Sports Sciences 26, 113–122.

Balazs, G.C., Pavey, G.J., Brelin, A.M., Pickett, A., Keblish, D.J., Rue, J.-P.H., 2015. Risk of anterior cruciate ligament injury in athletes on synthetic playing surfaces: a systematic review. The American Journal of Sports Medicine 43, 1798–1804.

Bardet, J.P., Sanchez, J., 2011. Soxhlet extraction determination of composition of synthetic soils. Geotechnical Testing Journal 34, 1–10.

Barrey, E., Landjerit, B., Wolter, R., 1991. Shock and vibration during the hoof impact on different track surfaces. Equine Exercise Physiology 3, 97–106.
Binnie, M.J., Dawson, B., Pinnington, H., Landers, G., Peeling, P., 2014. Sand training: a review of current research and practical applications. Journal of Sports Sciences 32, 8–15.
Bridge, J.W., Mahaffey, C.A., Peterson, M.L., 2014. Analytical test methods used to characterize granular composite sport surface materials. Applied Mechanics and Materials 440, 74–81.
Chateau, H., Robin, D., Falala, S., Pourcelot, P., Valette, J.-P., Ravary, B., Denoix, J.-M., Crevier-Denoix, N., 2009. Effects of a synthetic all-weather waxed track versus a crushed sand track on 3D acceleration of the front hoof in three horses trotting at high speed. Equine Veterinary Journal 41, 247–251.
Crevier-Denoix, N., Robin, D., Pourcelot, P., Falala, S., Holden, L., Estoup, P., Desquilbet, L., Denoix, J.-M., Chateau, H., 2010. Ground reaction force and kinematic analysis of limb loading on two different beach sand tracks in harness trotters. Equine Veterinary Journal 42 (Suppl. 38), 544–551.
Crevier-Denoix, N., Camus, M., Falala, S., Ravary-Plumioen, B., Douilly-Holden, L., Robin, D., Denoix, J.-M., Chateau, H., Pourcelot, P., 2013a. External loads on the leading and trailing forelimbs of a jumping horse at landing measured with a dynamometric horseshoe. Computer Methods in Biomechanics and Biomedical Engineering 16 (Suppl. 1), 145–146.
Crevier-Denoix, N., Pourcelot, P., Holden-Douilly, L., Camus, M., Falala, S., Ravary-Plumioen, B., Vergari, C., Desquilbet, L., Chateau, H., 2013b. Discrimination of two equine racing surfaces based on forelimb dynamic and hoof kinematic variables at the canter. The Veterinary Journal 198 (Suppl. 1), 124–129.
Crevier-Denoix, N., Munoz-Nates, F., Van Hamme, A., Camus, M., Emond, A.-L., Jerbi, H., Ravary-Plumioën, B., Chateau, H., Pourcelot, P., 2015. Biomechanical comparison between hybrid turf ('AirFibr' technology) and natural turf at landing after hurdle jumping in one horse. Computer Methods in Biomechanics and Biomedical Engineering 18 (Suppl. 1), 1916–1917.
Dixon, S., Fleming, P., James, I., Carré, M., 2015. The future of sports surfaces. In: Dixon, S., Fleming, P., James, I., Carré, M. (Eds.), The Science and Engineering of Sport Surfaces. Taylor and Francis, New York, pp. 226–233.
Durá, J., Hoyos, J., Lozano, L., Martínez, A., 1999. The effect of shock absorbing sports surfaces in jumping. Sports Engineering 2, 103–108.
Egenvall, A., Tranquille, C.A., Lönnell, A.C., Bitschnau, C., Oomen, A., Hernlund, E., Montavon, S., Franko, M.A., Murray, R.C., Weishaupt, M.A., et al., 2013. Days-lost to training and competition in relation to workload in 263 elite show-jumping horses in four European countries. Preventive Veterinary Medicine 112, 387–400.
Guisasola, I., James, I., Stiles, V., Dixon, S., 2010. Dynamic behaviour of soils used for natural turf sports surfaces. Sports Engineering 12, 111–122.
Gustås, P., Johnston, C., Roepstorff, L., Drevemo, S., 2001. In vivo transmission of impact shock waves in the distal forelimb of the horse. Equine Veterinary Journal (Suppl. 33), 11–15.
Johnston, C., Back, W., 2006. Hoof ground interaction: when biomechanical stimuli challenge the tissues of the distal limb. Equine Veterinary Journal 38, 634–641.
Kruse, L., Traulsen, I., Krieter, J., 2013. The use of a technical device for testing the sport-functional properties of riding surfaces. Journal of Equine Veterinary Science 33, 539–546.
Li, F., Peng, F., Li, J., Kongkitul, W., 2009. Strain rate effects on sand and its quantitative analysis. Journal of Central South University of Technology 16, 0658–0662.
Murray, R.C., Walters, J.M., Snart, H., Dyson, S.J., Parkin, T.D.H., 2010. Identification of risk factors for lameness in dressage horses. The Veterinary Journal 184, 27–36.
Minetti, A.E., Ardigò, L.P., Reinach, E., Saibene, F., 1999. The relationship between mechanical work and energy expenditure of locomotion in horses. The Journal of Experimental Biology 202, 2329–2338.
Nigg, B.M., 1990. The validity and relevance of tests used for the assessment of sports surfaces. Medicine and Science in Sports and Exercise 22, 131–139.
Orlande, O., Hobbs, S.J., Martin, J.H., Owen, A.G., Northrop, A.J., 2012. Measuring hoof slip of the leading limb on jump landing over two different equine arena surfaces. Comparative Exercise Physiology 8, 33–39.
Parkes, R.S.V., Witte, T.H., 2015. The foot-surface interaction and its impact on musculoskeletal adaptation and injury risk in the horse. Equine Veterinary Journal 47, 519–525.
Peterson, M.L., McIlwraith, C.W., Reiser, R.F., 2008. Development of a system for the in-situ characterisation of thoroughbred horse racing track surfaces. Biosystems Engineering 101, 260–269.
Peterson, M.L., Reiser, R.F., Kuo, P.H., Radford, D.W., McIlwraith, C.W., 2010. Effect of temperature on race times on a synthetic surface. Equine Veterinary Journal 42, 351–357.
Ratzlaff, M.H., Hyde, M.L., Hutton, D.V., Rathgeber, R.A., Balch, O.K., 1997. Interrelationships between moisture content of the track, dynamic properties of the track and the locomotor forces exerted by galloping horses. Journal of Equine Veterinary Science 17, 35–42.
Robin, D., Chateau, H., Pacquet, L., Falala, S., Valette, J.-P., Pourcelot, P., Ravary, B., Denoix, J.-M., Crevier-Denoix, N., 2009. Use of a 3D dynamometric horseshoe to assess the effects of an all-weather waxed track and a crushed sand track at high speed trot: preliminary study. Equine Veterinary Journal 41, 253–256.
Schamhardt, H.C., Merkens, H.W., Vogel, V., Willekens, C., 1993. External loads on the limbs of jumping horses at take-off and landing. American Journal of Veterinary Research 54, 675–680.
Setterbo, J.J., Garcia, T.C., Campbell, I.P., Reese, J.L., Morgan, J.M., Kim, S.Y., Hubbard, M., Stover, S.M., 2009. Hoof accelerations and ground reaction forces of Thoroughbred racehorses measured on dirt, synthetic, and turf track surfaces. American Journal of Veterinary Research 70, 1220–1229.
Setterbo, J.J., Yamaguchi, A., Hubbard, M., Upadhyaya, S.K., Stover, S.M., 2011. Effects of equine racetrack surface type, depth, boundary area, and harrowing on dynamic surface properties measured using a track-testing device in a laboratory setting. Sports Engineering 14, 119–137.
Starbuck, C., Damm, L., Clarke, J., Carré, M., Capel-Davis, J., Miller, S., Stiles, V., Dixon, S., 2016. The influence of tennis court surfaces on player perceptions and biomechanical response. Journal of Sports Science 34, 1627–1636.
Thomason, J.J., Peterson, M.L., 2008. Biomechanical and mechanical investigations of the hoof-track interface in racing horses. Veterinary Clinics of North America, Equine Practice 24, 53–77.
Tranquille, C., Walker, V., Hernlund, E., Egenvall, A., Roepstorff, L., Peterson, M.L., Murray, R.C., 2015. Effect of superficial harrowing on surface properties of sand with rubber and waxed-sand with fibre riding arena surfaces: a preliminary study. The Veterinary Journal 203, 59–64.
Wilson, A.M., McGuigan, M.P., Su, A., van Den Bogert, A.J., 2001. Horses damp the spring in their step. Nature 414, 895–899.
Witte, T.H., Hirst, C.V., Wilson, A.M., 2006. Effect of speed on stride parameters in racehorses at gallop in field conditions. Journal of Experimental Biology 209, 4389–4397.