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Large Temporal Variations of Functional Properties of Outdoor Equestrian Arena Surfaces and a New Concept of Evaluating Reactivity With Light Weight Deflectometer Settlement Curves

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ABSTRACT

Sports physiological properties of ten sand or sand-mineral outdoor arenas, five with vertical drainage systems and five with an ebb and flow like system were assessed over a period of 8 weeks. For each arena, the riding zone was spatially delineated, nine locations at medium to intensely used zones were selected by simple random sampling and used along the whole measurement period. A total of 72 values for the dynamic deflection modulus (*Evd*), attenuation (*s*/*v*), settlement (*s*) and moisture content (Vol %) were analyzed for each arena. A novel technique to analyze the settlement curves of the light weight deflectometer (LWD) to describe reactivity of the footing surface was introduced. Statistical testing was done by linear mixed models. Three of the five arenas with a vertical watering system were judged to be hard ($Evd > 20$ MN/m^2), whereas all five arenas with an ebb and flow like watering systems were medium hard ($Evd = 10–20$ MN/m^2) over the entire 8 weeks. Significant ($P < .01$) temporal differences in *Evd*, *s*/*v* and moisture were demonstrated for both watering systems; however, the spatial and temporal variations were much lower with the ebb-flow system. Temporal consistency in the parameters over the test weeks appeared to be a criterion for stability of the arena surface. The analysis of the settlement curves of the LWD showed that the slope symmetry has a large potential to describe the restoration of the energy of an equestrian surface than only the settlement, which requires further validation.

1. Introduction

Horses move in training and during competitions on different surfaces, which absorb the impact forces on the hooves, the limbs, and the entire horse body differently [1–3].

Safety and quality standards for equestrian surfaces have been developed based on objective, repeatable measurements and ideal properties of riding arena surfaces have increasingly become the subject of scientific research in recent years [4,5]. Equestrian surface functional properties and characteristics have been described using the terms of impact firmness, cushioning, elasticity, grip, and regularity [4] and are part of an international standard testing with the Orono biomechanical surface tester (OBST) under Fédération Équestre Internationale (FEI) guides [4,5] and American Society for Testing and Materials (ASTM) E2835-11 [6]. Objective evaluation criteria measuring the functional surface properties of impact firmness, and to a lesser extent, cushioning and grip were significantly and positively associated with top level riders' assessment of the same properties [7]. However, subjective riders' assessment displayed a large variation, and it was concluded that standardized mechanical equipment offers more consistent comparisons between surfaces [7]. There is no generally valid description of the optimum footing condition for horses. Since demands of horses and riders on the riding surface vary greatly from discipline to discipline, it must be possible to adapt the requirements and limit values individually. In addition, no test device or test method has yet been agreed on as a standard. Test devices measure parameters differently, so that designation of properties and conclusions differ depending on used test device.

Ideally, a testing device simulates impact and speed produced during the horse hoof-surface interaction [8]. However, the OBST,

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the device applied by numerous authors [4,5,7,8] is expensive, complex and not always readily available.

A Light Weight Deflectometer (LWD) is a portable device that measures the onsite dynamic deflection modulus (*Evd*) reflecting the deformability of the surface under a defined vertical impact load Tmax, also described as stiffness or hardness [6,9–11]. A major advantage is that the dynamic plate load test is transportable and can be performed by a single person. The settlement (*s*), indicates the sum of the plastic and elastic deformation of the ground substrate due to the load of the LWD and can be related to the depth of hoof penetration.

The size of a 150 mm loading plate of the LWD corresponds approximately to the size of 142 mm of a front hoof of a warmblood horse (Hanoverian breed) at its widest point [12]. The 10 kg weight of the LWD drop plate drops from a height of 72 cm onto the plate to ensure the required maximum impact force of 7.07 kN (TP BF-StB Part B 8.3, 1992). This impact force is thus in the range of 6.5 kN to 8.6 kN which the horse applies to the ground when cantering [13]. The mass dropped by the LWD approximates therefore a deflection of the surface consistent with the energy of the cantering horse.

Supported by mechanical equipment, the settlement or deflection curves of the LWD describe the timing between deformation of the surface during loading and the timing of any elastic recovery [6,9–11]. The ratio of settlement (*s, mm*) and timing of penetration (*v, ms*) is reflecting the degree of compatibility or the attenuation (*s/v*) of the respective surface [6,9–11]. How elastic or reactive an equestrian surface reacts to the horse's movements is so far essentially determined by the impressions of the respective riders or by analyzing the horse's gait pattern [4]. Senseney and Mooney [14] showed that the LDW with a loading plate of a diameter of 300 mm offers a 600 mm investigation depth below plate level and a 150 mm diameter loading plate results in 300 mm investigation depth below plate level [14]. The LWD allows to assess surface functional properties of the footing layer, which usually has a depth of 10 to 30 cm [15], and partly also of the base layer. Therefore, LWD is another standard method able to separate the effects of layered systems [14]. Since different layers of an equestrian surface have a substantial influence on riding properties, these results may also be of interest.

In Switzerland, most show jumping competitions are held on sand-mineral or sand-fiber arenas. Similar conditions were described in Sweden, where a survey showed that sand-mineral arenas were most common outdoors and sand-woodchips arenas most common indoors followed by sand-fiber arenas and some synthetic arenas [15]. Besides other factors different riding arena construction, materials, watering systems, maintenance management, environmental factors and type and frequency of use influence the local properties within and between riding arena surfaces' [8,16].

The aim of the present study was to assess the sports physiological properties over time and space of ten sand and sand fiber outdoor arenas, five with vertical drainage system and five with an ebb and flow like watering system. Weekly measurements were made at nine different locations on each of the ten arenas with the LWD for 2 months focusing on the spatial and temporal evolution within each site. To the best of our knowledge LWD settlement curves have only been analyzed up to the impact and the elastic rebound of the LWD mass remained so far unconsidered. We therefore hypothesized that the full evaluation of the settlement curves including the rebound speed of the mass serves as an objective method to describe the reactivity of an equestrian arena surface.

2. Materials and Methods

2.1. Sampling and Measurement Design

Ten outdoor riding arenas located in the east of Switzerland were included in the study and selected by type of irrigation system and material of the footing surface. The watering system of five arenas was by vertical drainage, all with water sprinklers, and of the other five arenas with an ebb and flow like system. The footing surface of the riding arenas consisted of quartz sand with fleece fibers, except two arenas, of which one consisted only of quartz sand without additives (vertical drainage system) and the other consisted of quartz sand with rubber additives (ebb and flow like irrigation system). The arenas were predominantly used for training purposes but also for show jumping or dressage events (Table 1).

The ten training arenas were examined weekly over a period of 8 weeks, beginning on August 23 and ending on October 13, 2021. Temperature [°C] and humidity data [%-sat]) were obtained retrospectively from four meteorological weather stations located near the selected arenas (stations Bad-Ragaz, Waedenswil, Siebnen and Arth [17]). Examination at each site was always carried out by the same person on the same weekday and at the same time of the day, resulting in different times of the day for each arena. Before the first examination in week 1, all arenas were maintained by dragging and harrowing. The riders and the personnel of the equine riding center were asked to keep a log of usage, further maintenance care and the amount of watering for vertical watering systems throughout the period.

Table 1
Background information of the 10 surveyed riding arenas.

Arena ID	Size Length and Width in (m)	Age (Years)	Show-Events Days per Year (#/a)	Watering system		Top Layer Type	Top Layer Thickness (cm)
				vertical	Ebb and Flow like system		
1	74 × 40	10	5–10	X		quartz sand + fibers	12.0–17.5
2	60 × 30	10	15–20	X		quartz sand + fibers	10.0–19.0
3	44 × 74	7	5–10	X		quartz sand + fleece chips	1.6–6.5
4	100 × 40	10	15–20	X		quartz sand + fibers	12.0–17.0
5	55 × 35	10	15–20	X		quartz sand, no additives	10.0–17.0
6	20 × 60	10	0		X	quartz sand + fleece chips	12.5–16.5
7	20 × 40	10	0		X	quartz sand + rubber chips	8.5–12.5
8	30 × 50	1	0		X	quartz sand + fleece chips	9.5–13.5
9	62 × 70	10	5-10		X	quartz sand + fleece fibers + chips	26.0–33.0
10	25 × 70	10	5-10		X	quartz sand + fleece fibers + chips	24.0–33.0

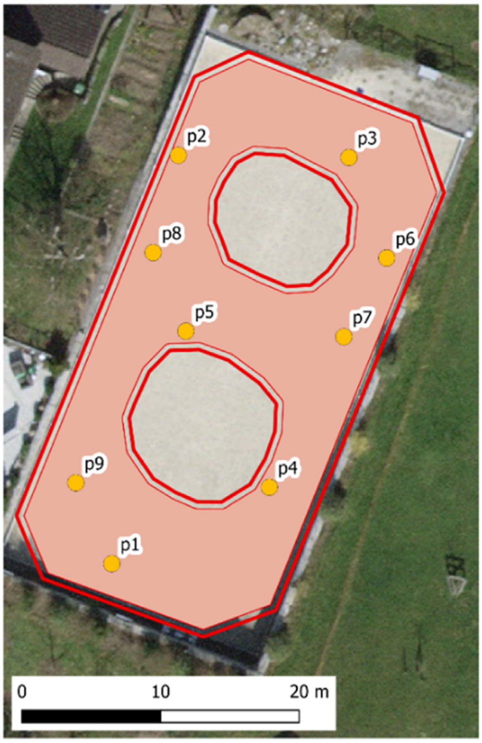

Fig. 1. Selection of measurement points by simple random sampling within the riding arena at site seven (labels: point ID, red thick line: delineation of medium to heavily used area, red thin line: inwards buffering of 0.5 m to avoid edge effects, red fill color: heavy use surface (data source background: SWISSIMAGE 10 cm [20]).

LWD measurements were performed weekly on all surfaces [9] with a loading plate of 150 mm diameter and a mass of 10 kg, application ASTM E2835-11 [6] and calibrated according to the Road and Transportation Research Association, Working Group Earthworks and Foundations (FGSV) [11]. All measurements were performed at nine sampling points chosen by simple random sampling [18] within medium to heavy used areas. For each arena the riding zone was spatially delineated in medium to heavily and rarely used zones [19] according to aerial images [20] and information of the arena owners. The medium to heavily used area was reduced by 0.5 m (inwards buffer) to avoid border effects linked to the accuracy of the riding area delineation from the aerial images (Fig. 1). Nine points were chosen at random under the condition of at least 5 m distance between the sampling points (Fig 1). The rarely used zones were not sampled. Measurements were repeated for each riding arena at the same positions located using an accurate real-time kinetics global navigation satellite system (RTK-GNSS) handheld receiver.

2.2. LWD Measures and Preprocessing

At each sampling location three impacts with the LWD load plate were measured. This was repeated three times which resulted in nine drops per sampling point. The LWD automatically generates an average value of three successive drops for the dynamic deflection modulus (*Evd*, [MN/m^2]), the attenuation (*s/v*, [ms]) and soil settlement (*s*, [mm]). Each drop of the LWD displays one settlement curve resulting in nine settlement curves per sampling point and measuring day. Based on data of the manufacturer ZORN Instruments GmbH [9] results of *Evd* and *s/v* were categorized for subsequent statistical analysis into three classes as follows:

1) Soft equestrian arena surface: *Evd* < 10 MN/m^2; *s/v* > 6 ms,

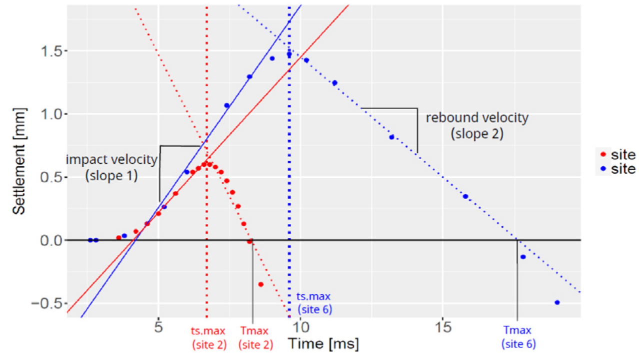

Fig. 2. Illustration of settlement curve analysis: impact velocity (slope 1) = approximate slope of the rising part of the settlement curve; rebound velocity (slope 2): approximate slope of the falling part of the curve; ts.max = time to the maximal rise; the settlement curve of site two represents an arena surface with large *Evd* (49.6 ± 19.2 MN/m^2) and site six an arena surface with an *Evd* within the target range of 10 to 20 MN/m^2 (18.7 ± 3.98).

2) Medium hard equestrian arena surface: *Evd* = 10–20 MN/m^2; *s/v* = 4–6 ms,
3) Hard equestrian arena surface: *Evd* >20 MN/m^2; *s/v* < 4 ms.

The target range for the tested training arenas in the present study was set at *Evd* = 10–20 MN/m^2 and *s/v* 4–6 ms

The settlement curves were analyzed to describe reactivity of the footing surface as illustrated in Fig. 2.

The curves were split into two sections, before and after the maximum depth reached by the LWD weight (ts.max). In more detail, each settlement curve consisted of readings of the plate position at different times (ms) and depth (mm). Each curve was established based on nine to 31 readings with time intervals ranging from 0.8 to 3.2 ms. To avoid outliers the first and last three readings and negative settlement values were rejected. The remaining readings were split into raising and falling part of the curve by their maximum settlement value (ts.max). To the values of each part an ordinary least squared linear regression was fitted to determine the impact and rebound velocity of the curve (slope 1 and slope 2). Linear regression approximated raising and falling part of the deflection curve well (goodness-of-fit R^2 between 0.95–0.99 except in a few cases with missing values). Finally, the time at which the plate returned to zero-ground-value (settlement = 0) was denoted Tmax. The symmetry of the curve was expressed as ratio of slope 1/slope 2 (slope symmetry). A small slope symmetry ratio indicates a higher reactivity, a large slope symmetry ratio a low reactivity of the arena surface. All parameters produced are presented with a respective explanation in Table 1.

2.3. On Site Property Measures of the Riding Arena Surface Materials (Moisture and $CaCO_3$ Content)

The moisture content (vol.%) of the footing layer was analyzed at all nine sampling points in each arena with three replicates using a moisture sensor (Moisture Meter, type HH2, Delta-T Devices Ltd, Cambridge, UK). The soil moisture content was analyzed to an approximate depth of 10 cm. For statistical analysis, moisture values of the three replicates per sampling point were averaged. Ideal moisture contents for equestrian arenas were considered for subsequent interpretation as follows:

Ideal moisture content for equestrian arenas as recommended by the manufacturer (Parkway, personnel communication) were

- 11.5 to 24.5 vol.-% for arenas with vertical watering systems.
- 36-46 vol.-% for arenas with an ebb and flow like systems.

The conversion factor used to convert gravimetric moisture to volumetric moisture was 1.44 for sandy soils [21], based on the assumption of relatively consistent bulk density for clean sand. All riding arena sand surfaces were tested for carbonate content ($CaCO_3$) using the HCL–quick test method [6].

2.4. Particle Size Distribution

To measure particle size distribution [22] samples of 5 to 7 kg were taken from the top layer at each of the nine sampling points of arenas ID 1 to 10. The samples were split into six subsample splitters (RT 12.5, Retsch GmbH, Haan, Germany). Subsamples of ca. 1 kg of each sample were dried at 105°C for 24 hours in a drying chamber with forced convection (FD 115 Binder GmbH, Tuttlingen, Germany). Dry sieving was performed with a sieve shaker (HAVER EML digital plus, 59302 Oelde, Germany) using the following sieves: >4.0 mm, 2mm, 1 to 3 mm, 0.63 to 1mm, 0.5 to 0.63 mm, 0.18 to 0.5 mm, 0.106 to 0.18 mm, 0.06 to 0.106 mm and <0.05 mm. The percentages the particle size fractions of the sample were determined. Aggregates such as fleece and rubber were removed manually after screening and not included in the particle size fractions.

2.5. Statistical Analysis

For statistical analysis of dynamic deflection modulus, attenuation, and settlement, the data of 2,160 settlement curves were considered (10 arenas with nine sampling points and three LWD repetitions at each point with 8 weekly revisits). Due to the longitudinal structure and the repeated measures, linear mixed models [23] were used (function lmer, package lme4, version 1.1–32 [24]). Prior to further analysis the effect of repeated strokes [25], here in relation to the 3 × 3 repetitions with the LWD, was investigated in the mixed model and was found to be not significant ($P >$ .05). Measurement week (eight levels) and type of drainage system (two levels, vertical and ebb flow like) were defined as fixed effects and arena and sampling points were included as nested random effects. To compare the 8 weeks at each site we fitted linear mixed models for each site separately with measurement week as fixed effect and the sampling points as random effects. Normal distribution of model residuals was verified by visual inspection of quantile-quantile and Tukey-Anscombe plots [26]. Plots of model residuals indicated no violation of model assumptions for attenuation and settlement. Residuals of *Evd* were positively skewed, thus transformation by natural logarithm was performed prior to fitting the mixed models. If the fixed effects coefficients were significantly non-zero (log-ratio test, P-value < .05) a pairwise Tukey-HSD test was performed (function glht, package multcomp, version 1.4–22 [27]). All statistical analysis were performed in R environment for statistical computing [28].

3. Results

3.1. Overall Data of the Arenas

According to the data of the five weather stations, the average temperature, precipitation and air humidity were 17.8°C (17.5°C–17.9°C), 219 mm and 85% in August, 16.6°C (16.5°C–16.8°C), 52 mm and 84% in September and 9.85°C (9.5°C–10.5°C), 45 mm and 85% in October 2021 [17]. Prior to the first measurement with the LWD in August 2021, there was heavy rainfall, as well as between weeks four and five of the measurement series [17].

Measurement results of dynamic deflection modulus (*Evd*), attenuation (*s/v*), settlement (*s*) and moisture (Vol %) are presented in Table 3 and of particle size distribution in percentage of solid particle dry weight per particle size in Table 4. Sand of arenas ID one, two, and 4 reacted strongly to the HCL quick test which indicated a $CaCO_3$ content between 2% and 10 %. All other arenas showed a light reacting by applying HCL representing less than 2 % carbonates in the sand.

3.2. Temporal Variations of Dynamic Deflection Modulus (Evd), Attenuation (s/v) and Moisture Content

Figs. 3 to 5 show changes in dynamic deflection modulus, attenuation, and moisture content over the measurement period of 8 weeks. Three of the five arenas with a vertical watering system were judged to be hard with *Evd* values larger than 20 MN/m^3, sites ID's 1, 2 and 4 for almost all measurements. These three arenas were the only ones with quartz sand and fiber top layers and showed very large variations of measurements over time, but also within the arena. In the third week at site ID 2 an extremely large

Table 2
Parameters produced with the light weight deflectometer (LWD).

Parameter	Abbreviation	Unit	Calculation form the LWD	Explanation
Dynamic deflection modulus	*Evd*	MN/m^2	Evd [MN/m^2] = 1.5–r_{plate} [m]–σ [MN/m^2]/ s [m] Evd = 1.5–0.075–0.4/ s = 0.045/s[m] = 45/ s [mm]	reflecting the deformability of the soil under a defined vertical impact load Tmax, also described as stiffness or hardness [9]
Attenuation	*s/v*	ms	s = settlement [mm] v = timing of penetration of the LWD plate [ms]	s/v = degree of compactibility, which gives information about whether the existing soil can be compacted further or not. It is an empiric value. Evaluation is only based on already compacted soil (in general: s/v < 3,5 no further compaction possible; s/v > 3,5 further compaction possible [9] As long as the arena surface can still become more compact due to the impact of weight, the energy can still be attenuated
Settlement	*s*	mm	Mean value of deflection	Indicates the sum of the plastic and elastic deformation of the ground substrate due to the load of the LWD and can be related to the depth of hoof penetration
Impact velocity	*Slope 1*	m/s	Slope analysis of the first part of the settlement curve until ts.max (Fig. 2)	Slope of first, rising part of the settlement curve–related to *Evd* and *s/v*
Rebound velocity	*Slope 2*	m/s	Slope analysis of the second part of the settlement curve until Tmax (Fig. 2)	Slope of second, rebounding part of the settlement curve, related to elastic recovery of the arena surface and restitution of the energy or reactivity of an arena surface
Reactivity	*Slope symmetry*		Ratio of slope 1 and 2	The slope symmetry as an indicator of reactivity of an arena surface

r_{plate} = radius of the plate of the LWD; σ = exerted pressure = 400 kPa (equivalent to 4 bar, or 0.4 MN/m^2); s = settlement of the arena surface.

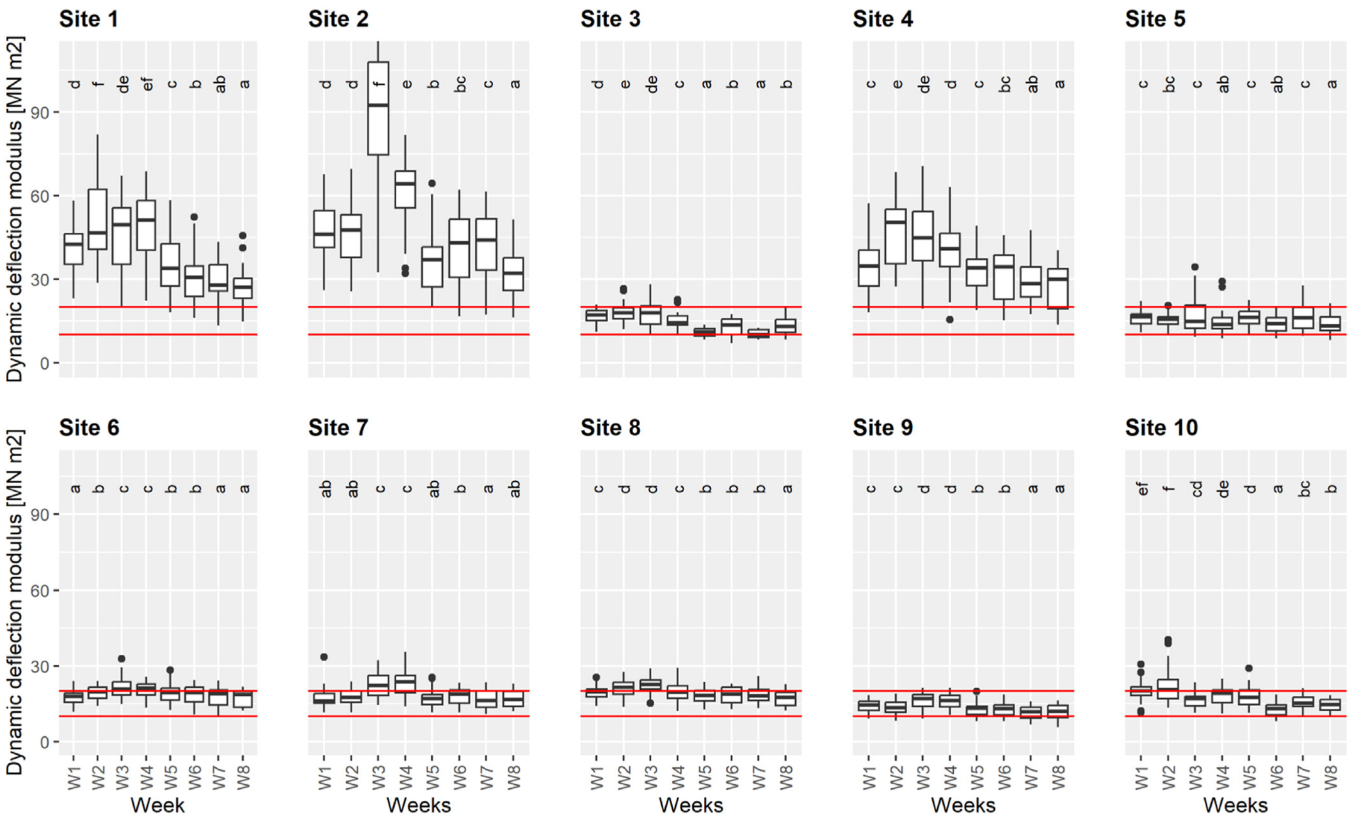

Fig. 3. Dynamic deflection modulus (*Evd*) over 8 weeks for the 10 arenas; horizontal red lines indicate target range of Evd = 10-20 MN/m^2, different superscripts (a-d) indicate significant differences (pairwise Tukey-HSD test for each site separately, p<0.01) between weeks. The tests were made separately for each site.

average of *Evd* of 90 MN/m^2 was observed. On the other hand, all of the five arenas (Fig. 3, ID's 6–10, bottom row) with ebb and flow like watering systems were within a medium hard range (*Evd* 10–20 MN/m^3) nearly over the entire 8 weeks. It was noticeable that all arenas with ebb and flow irrigation systems had more constant values over time and seem to have a better buffering of environmental conditions.

Similarly, attenuation was on average low (s/v < 4 ms) for same three out of five sites with vertical irrigation, while average attenuation of sites with ebb and flow like systems (Fig. 4, bottom row) remained in the range of s/v = 4 to 6 ms over all 8 weeks. Overall, standard deviations (Table 3, Fig. 4) of attenuation were much larger for the vertical irrigation than for the ebb and flow like watering system. Fixed effect coefficients of drainage system were not significant (log-ratio test P > .01) as the mixed effects models show a clear dominant effect of measurement week. Also, for arenas within the defined target range and with small variations there were significant differences over time (see superscript letters in Figs. 3 and 4). Log-ratio tests became significant mostly because of the small variability within the arena while magnitude of changes (value of model coefficient) remained small expect for sites ID one, 2 and four. Soil moisture (Fig. 5) was variable over time showing no clear trend between drainage system.

3.3. Spatial Variation of the Properties Within a Single Arena

Figs. 3 and 4 indicate very large spatial variation of dynamic deflection modulus and attenuation within the arena measured within maybe 1 hour for already mentioned sites ID's one, 2 and four. Spatial variations in the dynamic deflection modulus and reactivity expressed as ratio of impact and rebound velocity of the settlement curve (slope symmetry ratio) are illustrated for arena ID 7 and 2 in Figs. 6 and 7, respectively. Arena ID 7 showed softer conditions in week seven than in week four. Slope symmetry ratios in week 4 were lower than in week 7, indicating that surface recovery was greater in week four than in week seven. Fig. 7 illustrates the conditions in week four and seven of arena ID 2 with very hard to hard training surfaces. Although the *Evd* in arena ID 2 decreased in week 7 slope symmetry remained unchanged or even slightly increased representing the high reactivity of a hard arena surface. Arenas with large values of *Evd* and low values of s/v also show a large variability, also illustrated based on the height of the boxplot within a given week (Figs. 3 and 4). Or vice versa, the lower the boxplot in Figs. 3 and 4, the higher the spatial homogeneity of the riding arena.

3.4. Evaluation of the Concept of Reactivity

Overall descriptive statistics derived from the settlement curves to describe reactivity of weekly measurements from riding arena ID 1 to 10 in 2 months are presented in Table 5. Small impact velocity (slope 1) values mean low settlement (mm) in which case the settlement curve rebounds fast (slope 2). Short response time after ts.max means fast restitution of the energy expressed as a small rebound velocity (slope 2, absolute value). It can be stated that the larger the dynamic deflection modulus and the smaller the attenuation, the smaller the impact velocity (slope 1) and the ratio between impact and rebound velocity (slope symmetry ratio). The relationship was not linear, rather a cut-off point became evident, but only for arenas with large overall *Evd*. If the symmetry of the settlement curve expressed as ratio of impact to rebound velocity (slope 1/slope 2) is lower than two, the arena surface is extremely hard. Hard surfaces have falling settlement curve slopes larger than 0.3 m/s (absolute value) during the rebound. Consid-

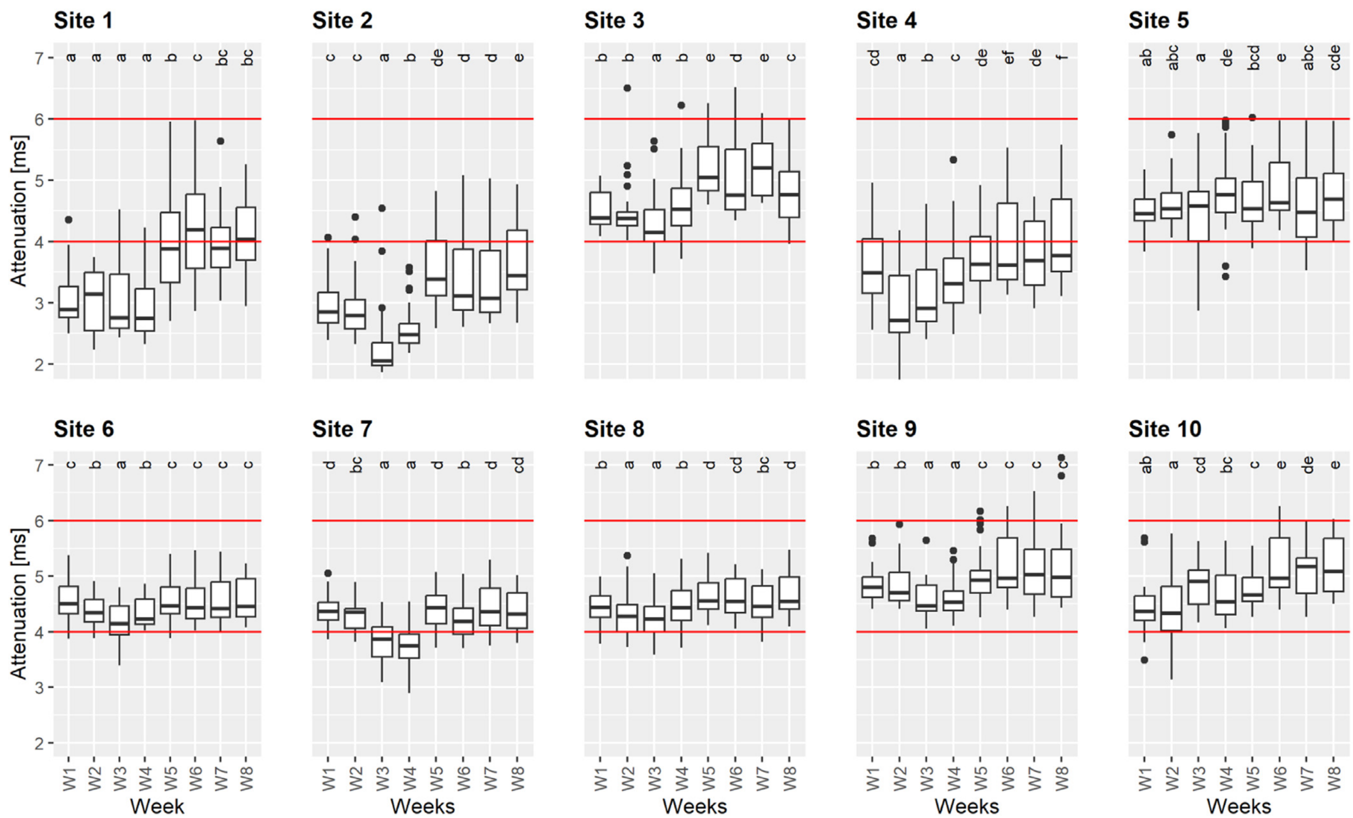

Fig. 4. Attenuation (s/v) over 8 weeks for the 10 arenas; horizontal red lines indicate target range of s/v = 4 to 6 ms, different superscripts (a–d) indicate significant differences (pairwise Tukey-HSD test for each site separately, P < .01) between test weeks.

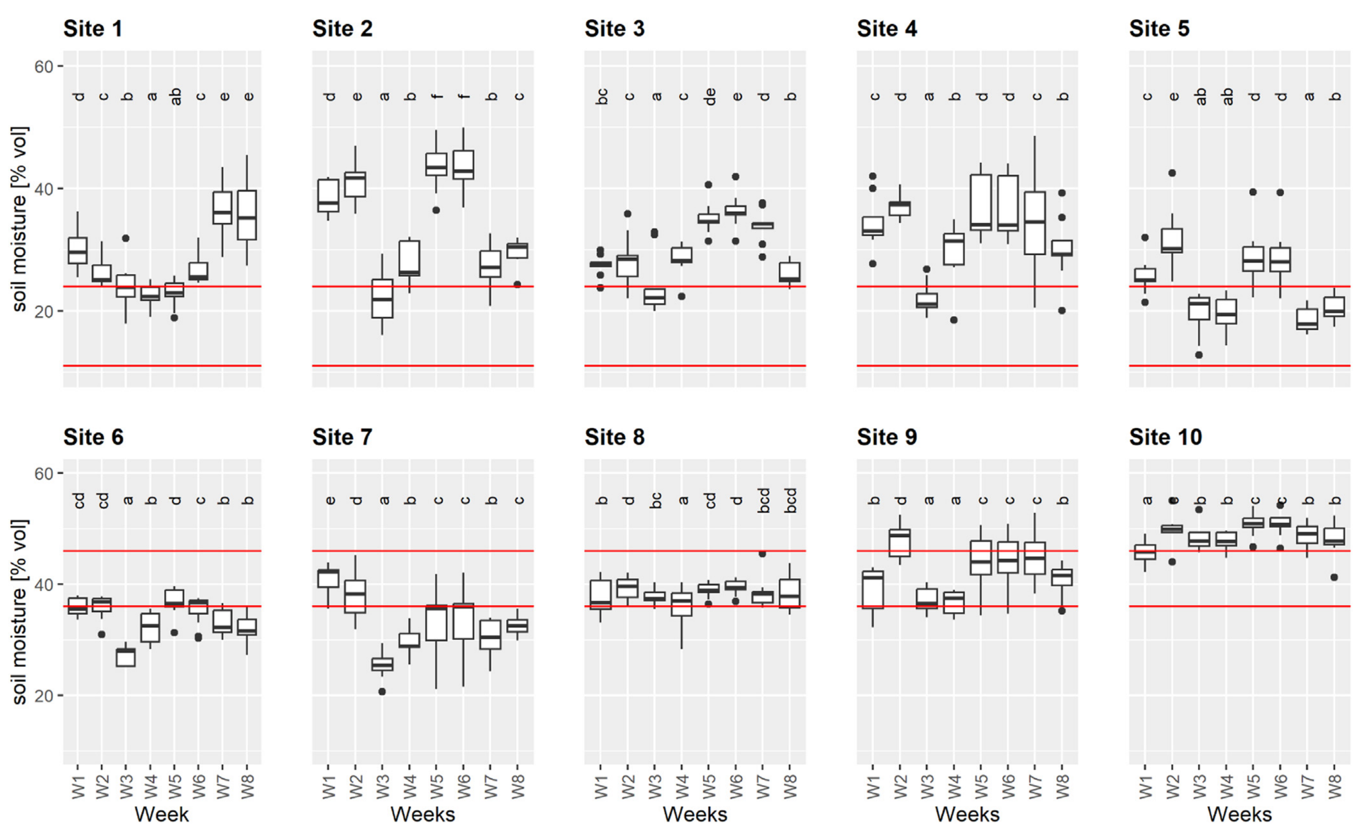

Fig. 5. Volumetric moisture % over 8 weeks for the 10 arenas; horizontal red lines indicate ideal range for arenas with vertical watering systems (1–5) and ebb and flow like watering systems (6–10) as recommended by the manufacturers, different superscripts (a–d) indicate significant differences (pairwise Tukey-HSD test for each site separately, P < .01) between test weeks.

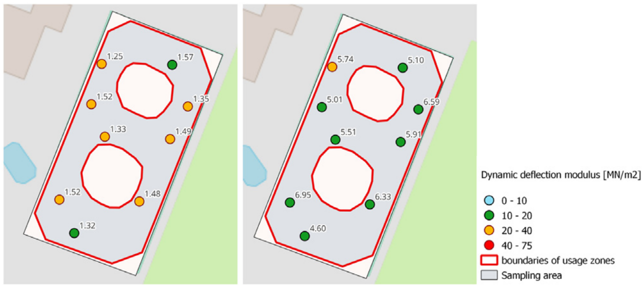

Fig. 6. Spatial variations of the dynamic deflection modulus (Evd, MN/m^2) and reactivity expressed as slope Symmetry ratio of arena ID 7 in week four (left) compared to week seven (right, value above sampling points: slope symmetry computed as ratio of raising and falling slope of the settlement curve, mean of three repetitions).

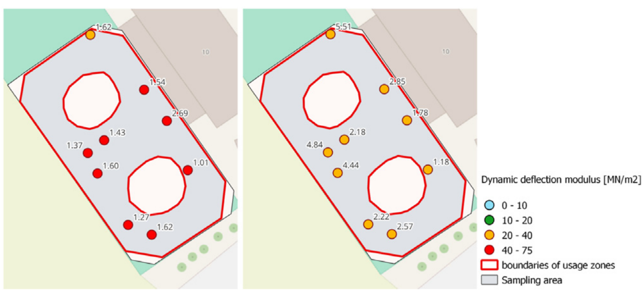

Fig. 7. Spatial variations in the dynamic deflection modulus (Evd, MN/m^2) and reactivity expressed as slope Symmetry ratio in arena ID 2 in week four (left) compared to week seven (right, value above sampling points: slope symmetry computed as ratio of raising and falling slope of the settlement curve, mean of three repetitions).

ering the ratio between the rising and falling slopes of the curve, they vary greatly depending on the site and the week (Fig. 8). Absolute slopes depend on time and settlement, hence individual values of increasing and decreasing slope are describing reactivity less well than slope symmetry ratio. We found deflection curves with smaller slope symmetry ratios for hard surfaces meaning such surfaces result in fast rebound. In contrast, soft surfaces resulted in larger slope ratios with a slower rebound. It is unlikely that there are very hard arena surfaces (*Evd* > 20 MN/m^2) above slope symmetry ratio of two, but there exist surfaces with low slope symmetry ratios and with an *Evd* within the target range (*Evd* 10-20 MN/m^2). The latter would be a good combination of hardness of the surface and its reactivity.

4. Discussion

4.1. Practical Implementation of Arena Testing

Selection of sampling points by simple random sampling allowed for unbiased evaluation of each arena. It was possible to locate the sampling points by a GNSS handheld again after a week without needing to mark these points in the arena otherwise. Using GNSS positioning had the advantage that the riding arena could be used between two test weeks without the risk of damaging possible markings. However, the accuracy of the tracking depended on signal strength and satellite positions but allowed to locate the sampling points within an arena in an acceptable radius of about 50 cm at reasonable time. To best approximate a horses hoof all equine training surfaces were tested with the LWD with a loading plate of 150 mm diameter and a weight of 10 kg [14].

4.2. Arena Material Type and Particle Size Distribution

Arena construction, base type, type and shape of additives, usage patterns, arena surface age, type and location are limiting factors when extrapolating the results of the surface's mechanical behavior to other arenas [16,29]. In this study, five outdoor arenas with vertical watering system and five with an ebb and flow like watering system were investigated, but all had a quartz sand top layer with fleece fiber or fleece chips additives. Only one arena (ID five) was without additives and quartz sand only and one with quartz sand and rubber chips additives. Regarding the arena surface age, eight arenas were in use for 10 years, 1 for 7 years (ID seven) and one arena (ID eight) was newly constructed and only in use for 1 year. Although there were similarities between the 10 arenas, there are limitations as there remain many unconsidered factors which influence the mechanical behavior of the surfaces differently. Therefore, our observations focused on temporal and spatial changes within an arena.

Already during the process of sampling of all arenas for laboratory analysis arena ID 2 was perceived as the hardest arena surface. Hobbs et al, [4] point to manufacturer recommendations of

Table 3
Descriptive statistics of dynamic deflection modulus, attenuation, settlement, and moisture (mean ± standard deviation, range) of 8 weekly measurements at nine sampling points with three repetitions for each of the ten riding arenas (ID 1–10, n = 72).

Arena ID	Dynamic Deflection Modulus Evd, MN/m^2	Attenuation s/v, ms	Settlement mm	Moisture Vol.-%
1	39.0 ± 11.3	3.53 ±0.70	1.32 ± 0.39	28.2 ± 6.20
	21.0–70.9	2.35–6.72	0.64–2.23	17.9–45.5
2	49.6 ± 19.2	3.09 ± 0.55	1.03 ± 0.35	34.2 ± 8.63
	24.6 - 107	1.92–4.41	0.43–1.94	16.1–49.9
3	14.4 ± 3.45	4.77 ± 0.43	3.39 ± 0.77	29.9 ± 5.24
	9.20–23.6	3.83–5.75	1.92–4.91	20.0–41.9
4	36.3 ± 9.61	3.55 ± 0.50	1.40 ± 0.35	32.8 ± 6.94
	19.8–63.1	2.35–4.58	0.72–2.34	18.5–48.6
5	15.5 ± 3.81	4.65 ± 0.34	3.10 ± 0.56	24.2 ± 6.07
	10.1–27.3	3.46–5.27	1.83 - 4.53	12.7–42.5
6	18.9 ± 2.57	4.45 ± 0.24	2.48 ± 0.34	33.5 ± 3.68
	13.7–26.3	3.74–5.01	1.72–3.41	25.1–39.6
7	18.7 ± 3.98	4.21 ± 0.33	2.56 ± 0.48	32.8 ± 6.22
	12.5–30.7	3.21–4.80	1.47 - 3.62	20.6–45.3
8	19.3 ± 2.42	4.49 ± 0.24	2.41 ± 0.30	38.2 ± 2.67
	14.8–26.5	3.74–4.95	1.71–3.10	28.4–45.5
9	13.6 ± 2.70	4.93 ± 0.34	3.54 ± 0.77	41.7 ± 5.22
	8.33–19.9	4.34–5.87	2.26–5.78	32.2–52.9
10	17.1 ± 4.13	4.82 ± 0.44	2.82 ± 0.62	48.7 ± 2.81
	10.0–34.4	3.57–5.86	1.38–4.62	41.2–55.1

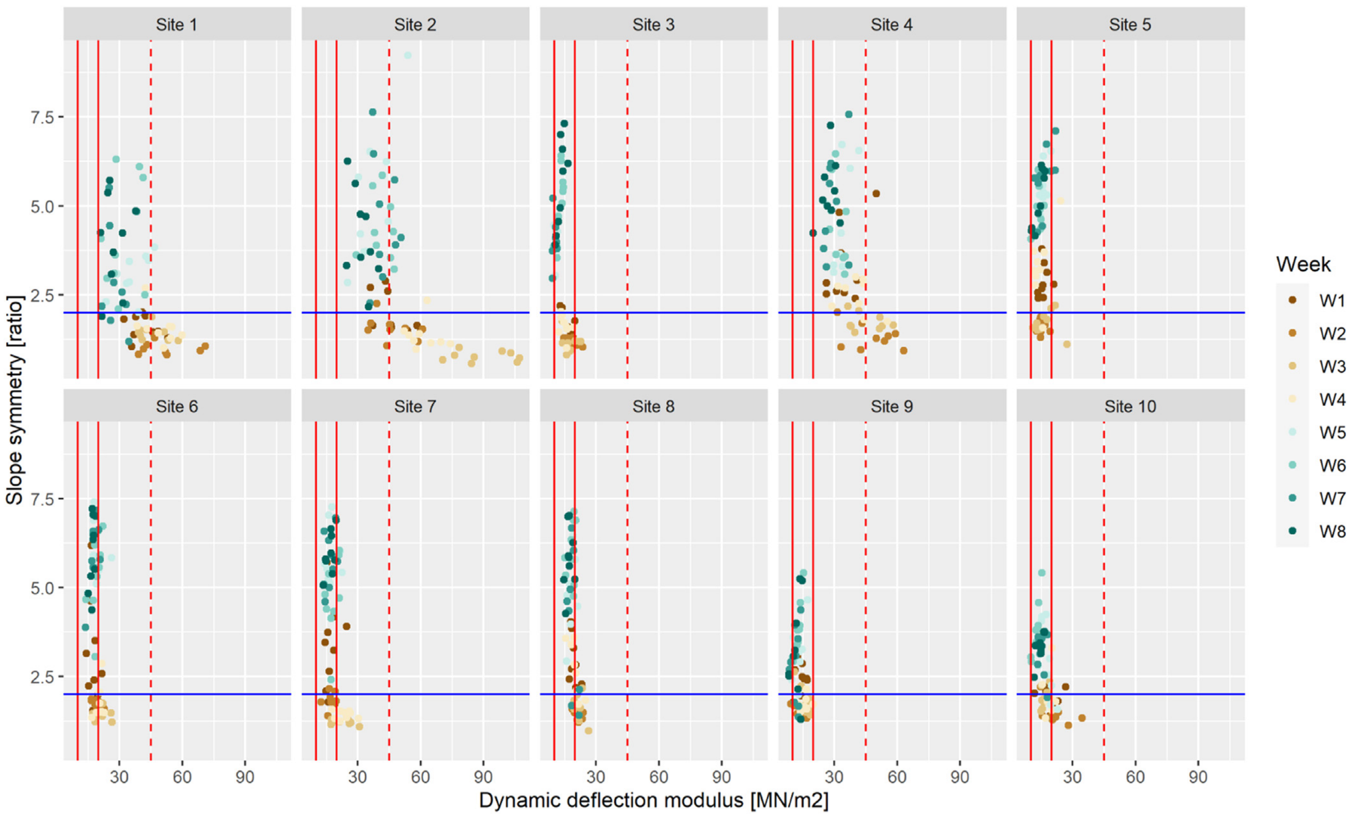

Fig. 8. Dynamic deflection modulus (Evd, MN/m^2) plotted against slope symmetry ratio colored by week of measurement (vertical solid red line: ideal Evd 10–20 MN/m^2, vertical dashed red line: Evd = 40 MN/m^2, horizontal solid blue line: slope symmetry ratio = 2). Hard surfaces rarely exhibit slope symmetry ratios larger than two while soft surfaces' symmetry ratios show a larger variation.

15% fine sand content below 0.063 mm in combination with synthetic aggregates to use for arena constructions. Herlund and Lönnell [5] showed that sandy materials with a broader grain size distribution which may include a larger proportion of very fine silt or clay and will have high shear strength but will compact, leading to a hard surface with poor drainage properties. This became evident for arena surfaces ID one, 2 and 4 with more variable grain size distributions (Table 3). The heterogeneity probably leads to a more intense filling of the voids between the coarse particles and thus larger packing density.

4.3. Relation of Dynamic Deflection Modulus and Attenuation

Arena surfaces with higher values for the dynamic deflection modulus (*Evd* > 20 MN/m^2) had lower values for attenuation (*s/v* < 4 ms) and lower settlement (< 2 mm). Hobbs et al. [4] have shown that too much attenuation can compromise locomotory efficiency and reduce stride length, but surfaces with less attenuation tend to provide enhanced performances as more energy is returned from the ground.

A study with a LWD (300 mm loading plate) reported, that with increasing sand layer thickness (160 mm, 200 mm, and 300mm) the settlement value was decreasing [30]. This observation differed from the results of the present study, as arenas with a thicker sand layer did not necessarily have decreased settlement values (i.e., site ID 9 with 26–33 cm layer thickness, Table 1, 2). This might be explained by different particle sizes, the additives, different moisture contents and the size of the loading plate of the LWD.

4.4. Impact of Moisture Conditions

According to the recommendations of the manufacturer (Parkway, personnel communication), the moisture content of the ebb and flow like systems is expected to be between 36 to 46 Vol% and although significant differences occurred between weeks, the variation was smaller for this irrigation system. In this study, arenas with vertical watering systems had a higher mean volumetric moisture content (24.2 ± 6.07 – 34.2 ± 8.63 Vol%) than proposed by Ratzlaff et al. [31] with 11.5–24.5 Vol%. The study of Holt et al. [32] implied that a surface with higher moisture content (19.08 % = 27.47 Vol%) and medium surface density would generate the most favorable hoof-surface interaction when considering performance and risk injury.

According to the usage log of the riders and the personal of the equine riding centers, the arena ID 1 was muddy and arena ID 2 formed surface ponds after rainfall between week four and five. For all arenas, rainfall was noticeable through a change in of dynamic deflection modulus, attenuation, and moisture. For nine out of ten arenas these changes from week 4 to week 5 were statistically significant (Figs. 3 to 5). In previous studies it has been demonstrated that environmental factors and adverse weather during testing alter the properties of racing surfaces [31,33]. Overall, the magnitude of changes was small for all ebb and flow like systems which thus appeared to be less affected by external weather conditions. Three out of five vertically drained arenas showed very variable conditions. We allow for a tentative conclusion that vertical drainage in combination with calcareous top layer material are more prone to variations. Most extreme values were observed in arena ID 2. This arena was muddy in week 1 and 2 due to the previous rainfalls and had been maintained by harrowing after week 2. Dynamic deflection modulus of arena ID 2 increased then in week 3 above 80 MN/m^2 which corresponded to a surface hardness of a highway [9]. The arena ID 4 was also very wet, whereas the arena ID 5 located at the study site was much dryer. The surface of Arena ID 5 was described as more lively and coarser from the

Table 4
Percentage of solid particle dry weight for each of the ten riding arenas (ID 1–10, mixed sample of nine aliquots taken at the nine sampling points, fleece and fiber additives had been removed before sieving).

Arena ID	Sieving Size (mm) >4	2–4	1–2	0.63–1.0	0.5–0.63	0.18–0.5	0.106–0.18	0.06–0.106	< 0.05
1	22.19	0.33	1.126	0.81	0.82	54.68	16.34	2.62	0.96
2	34.00	0.23	0.70	0.45	1.09	39.99	18.60	3.82	1.11
3	0.96	0.80	3.90	5.30	6.62	54.81	21.06	5.41	1.13
4	12.89	0.26	0.37	0.41	1.07	78.63	4.66	1.41	0.32
5	16.84	3.77	11.66	10.27	8.75	39.56	6.29	2.40	0.46
6	24.14	0.10	0.26	0.18	0.25	24.85	44.15	1.53	0.55
7	17.43	0.02	0.07	0.09	0.12	39.89	39.15	2.68	0.56
8	2.58	0.17	0.17	0.15	0.25	35.19	56.78	3.60	1.11
9	3.75	0.08	0.15	1.30	4.01	81.38	8.71	0.41	0.21
10	1.61	0.07	0.11	0.05	0.06	82.45	15.13	0.31	0.21

Table 5
Descriptive statistics of variables derived from the settlement curves to describe reactivity (mean ± standard deviation, range) of 8 weekly measurements at nine sampling points with three repetitions for each of the 10 riding arenas (ID 1–10, n = 2,160).

Arena ID	Impact velocity slope 1	Rebound velocity slope 2	Ratio slope 1 / slope 2 (slope symmetry)	ts.max	Tmax
1	0.26 ± 0.04	-0.14 ± 0.07	2.46 ± 1.45	9.92 ± 2.17	22.2 ± 13.1
	0.19–0.38	−0.30 to −0.04	0.81–6.31	6.98–15.7	9.27–49.8
2	0.24 ± 0.05	−0.12 ± 0.07	3.00 ± 1.96	9.07 ± 1.70	26.4 ± 16.6
	0.15–0.37	−0.32 to −0.02	0.57–9.22	6.44–12.4	7.62–49.8
3	0.54 ± 0.07	−0.26 ± 0.13	3.04 ± 1.86	11.2 ± 1.05	21.5 ± 6.11
	0.37–0.68	−0.56 to −0.08	0.82–7.30	9.57–14.1	12.7–36.2
4	0.28 ± 0.04	−0.11 ± 0.06	3.55 ± 1.76	9.51 ± 1.00	25.8 ± 12.2
	0.21–0.37	−0.29 to −0.03	0.93–7.57	7.22–11.8	9.49–49.8
5	0.51 ± 0.06	−0.18 ± 0.10	3.89 ± 1.74	10.9 ± 0.59	23.0 ± 4.59
	0.38–0.65	−0.42 - - 0.06	1.11–7.10	9.04–12.5	13.1–34.4
6	0.43 ± 0.04	−0.16 ± 0.09	3.95 ± 2.19	10.6 ± 0.58	21.3 ± 4.32
	0.33–0.53	−0.36 to −0.06	1.22–7.40	9.46–13.0	13.2–34.0
7	0.46 ± 0.06	−0.18 ± 0.11	3.75 ± 2.06	10.3 ± 0.69	18.8 ± 3.76
	0.35–0.62	−0.44 to −0.06	1.08–7.27	8.60–12.2	10.7–24.6
8	0.42 ± 0.03	−0.16 ± 0.08	3.68 ± 1.92	10.6 ± 0.48	20.9 ± 4.43
	0.34–0.49	- 0.37 to −0.06	0.97–7.14	9.33–11.5	11.9–29.7
9	0.54 ± 0.07	−0.25 ± 0.08	2.57 ± 1.06	11.5 ± 0.76	23.3 ± 6.22
	0.41–0.70	−0.43 to −0.10	1.29 5.41	10.2–13.0	15.0–42.5
10	0.45 ± 0.06	−0.20 ± 0.06	2.60 ± 0.99	11.2 ± 0.91	25.2 ± 9.96
	0.29–0.64	−0.36 to −0.11	1.12–5.41	8.98–13.2	13.5–49.8

sand in comparison to arena ID 4 with very fine and compacted sand.

The fluctuations of the surface mechanical behavior over time were best visible for arenas ID 1, 2, 4 with vertical irrigation and positive HCL quick test for $CaCO_3$ indicating one factor of reduced water drainage. In addition, the high carbonate content contributes to cementing between the particles as the top layer material dries, which is particularly noticeable in weeks 3 of ID 1, 2 and 4.

4.5. Development of Arena Properties Over Time and Spatial Variations

The arenas with vertical irrigation showed more fluctuations in the measured values than the arenas with the ebb and flow like watering system. The time after the last surface maintenance session and the utilization intensity have also been shown to influence the functional arena surface properties significantly over time [34]. Arenas with vertical watering system in the present study had a higher utilization intensity with regard to show events, which might also partly explain the larger variability on the functional parameters. There were spatial differences in the mechanical properties between the nine sampling points within the arenas and within time. For example, arena ID 7 with an ebb and flow like watering system showed some spatial variations in week 4 and 7, but the arena surface conditions remained good to moderate over time. The arena ID 1 with a vertical watering system showed at the nine sampling locations spatial differences with large to very large surface dynamic deflection modulus and a very large reactivity expressed as slope symmetry ratio in week 4 which decreased at all locations in week 7. The frequency of usage of the sampling locations is one reason for the differences [34]. Another reason for spatial variations of mechanical properties was a difference in surface top layer depth. A difference of 5 cm in cushion depth significantly altered impact firmness in the study of Northrop et al. [8]. In the 10 arenas of the present study the differences in the top layer depth ranged from 4 to 9 cm, which might partly explain spatial differences in measured *Evd* values. Differences in reactivity (slope symmetry ratio) were higher in arena ID 1 with the vertical irrigation system than in arena ID 7 with the ebb and flow like watering system. It has also been reported that ebb and flow like watering systems provide a degree of area elasticity which is influenced by the moisture content, rather than a point elasticity [16]. Overall, we conclude that arenas with in average harder surface conditions (high *Evd*, low *s/v*, small slope symmetries in arenas ID's 1, 2, 4) have large fluctuations in time and space (Figs. 3 and 4). Hence, horses are expected to encounter difficulties adapting to the large changes in mechanical properties during one training/event but also between the trainings/events. In future investigations, only few measurements resulting in high dynamic deflection modulus values can therefore be interpreted as an indication of large surface variability of an arena.

4.6. Settlement Curve Properties to Approximate Surface Elasticity

The evaluation of the settlement curves with the LWD to objectively assess the reactivity of a riding surface was another important objective of this study. The first part of the paper shows the spatial and temporal variations of the standard parameters given by the LWD. These parameters are calculated based on the deceleration speed and the vertical displacement depth of the falling mass. Only the first part of the LWD settlement curve is used. During the measurements the mass bounces back more or less strongly after the impact. If the mass bounces upwards almost to the top the ground can be considered as reactive. If it hardly bounces at all the ground absorbs a large part of the energy. Dynamic deflection modulus and attenuation analyzed from LWD output [9] relates to the impact velocity (slope 1 in Fig. 2) of the settlement curve. The second part of the curve after the ground contact of the mass in the present study represented by the rebound velocity (slope 2 in Fig. 2) relates to different mechanical properties that are not linearly correlated with default attributes (Fig. 8). The response time of the rebound (slope 2) is related to the natural frequency of the limb, the surface, and the gait frequency. If elastic recovery occurs too soon, it will impose additional forces that must be dissipated by the limbs [31], whereas if it is well timed it may reduce the energy input required from the horse to maintain momentum. Rebound velocity was very fast for arenas ID 1,2 and 4 where the arena surface was extremely hard. The results in Fig. 8 show that an upper limit of hardness is reached when the slope symmetry is less than 2. Arena surfaces that are too hard are therefore additionally characterized. For arenas with an *Evd* in a range between 10 and 20 MN/m^2, the symmetries of the curves show a larger variation. As there are symmetries close to 2 also in arena surfaces with a *Evd* between 10 and 20 MN/m^2, it is likely that the yielding rebound is better with symmetries closer to 2 than to 4 or 5. Analyzing rebound by falling slopes of the settlement curve allows the selection of equestrian surfaces with a correct hardness and a good restitution of the energy. We would like to point out that symmetry values larger than two were not measured on very hard arena surfaces with a *Evd* larger than 45 MN/m^2. If the weeks of the individual sites are compared, it becomes clear that the surfaces of some sites are still too hard, but that those with an *Evd* within the target range show a great variability in reactivity. Therefore, we suggest that slope symmetry ratio above two but as well not to large i.e., too soft constitute an optimum for an arena surface being not too hard but still having optimal elastic rebound properties. The upper limit of optimal slope symmetry ratio would still have to be determined with really soft arena surfaces (*Evd* $<$ 10 MN/m^2) which were not represented in this study. The slope symmetry ratio has a potential to describe the restoration of the energy of an arena surface better than only the settlement, which requires further validation. However, mechanical testing systems have limitations as they may not accurately represent biomechanics of a living human or animal [3].

5. Conclusion

The study showed that there were significant differences in the functional surface properties of the outdoor arenas over the test weeks, to varying degrees depending mainly on the irrigation system, carbonate content in combination with moisture of the top layer material and the variability of particle size distribution. Temporal and spatial consistency in *Evd, s/v* and moisture over the test weeks appeared to be a criterion for the stability of the arena surface. We were able to demonstrate that a single analysis is not sufficient to fully characterize the buffering capacity of an arena surface. Interpretation requires consideration of grain size distribution, moisture, and carbonate content. A large variety of particle sizes and with carbonates present may lead to very firm conditions of arena surfaces with large variability within the arena and over time. Injury risks may therefore not just be increased by hardness but also by the large variability of the surface.

The analysis of the settlement curves of the LWD facilitated the quantitative description of the reactivity of the respective arena surfaces. Quantifying symmetry by approximating raising and falling slopes of the settlement curve seems to be a useful approach to describe the energy returned by a riding surface. To fully relate the newly presented settlement curve properties to default used *Evd* and *s/v* also soft arena surfaces would need to be included in future studies. In addition, these new properties would need to be related to riders' experiences as well as to injury risk and biomechanics of the horse.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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