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Spatial variation of the physical and biomechanical properties within an equestrian arena surface

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Abstract

There is limited information about spatial variation of equestrian arena surfaces despite unequivocal evidence to suggest that lack of uniformity increases risk of injury. Spatial differences in the functional properties of an arena are likely to be due to a number of intrinsic and extrinsic characteristics including variation in the physical properties of the surface. The aim of this work was to examine spatial variation of peak load (cushioning) across an arena surface and investigate the influence that physical properties had on these variations using Principal Component Analysis. Sampling (*n*=61) of a 20 m by 65 m indoor synthetic equestrian arena surface occurred in one day using an Orono biomechanical surface tester (OBST). The OBST was used at every location to measure peak load (dropped twice on the same point). A 200 g sample of the surface was taken from the point of impact (at every location) and the physical properties were assessed in the laboratory. Samples were oven dried at 45^0 C for 24 hours in order to measure moisture content and percentage binder was quantified using Soxhlet extraction. Sand particle size distribution were determined using sieving and sedimentation methods and percentage organic matter was achieved by burning off organic material using a muffle furnace at 440^0 C. The surface was characterized by three principal components (PC1, PC2 and PC3). Peak load and moisture were the first principal components that accounted for 41% of surface variation. Percentage organic matter and percentage binder were identified as PC2 (20%) and PC3 (18%) respectively. This highlights their respective importance in surface variation. There was a moderate negative correlation between moisture and peak load (r_s = 54%; P<0.0001) however cluster analysis revealed that peak load and moisture were grouped into five areas of similarity that corresponded to sample location, reinforced using an ANOVA (P<0.0001). The findings demonstrate an effective method of assessing uniformity and additionally, identify physical factors relevant to the load carrying capacity of this specific surface. Uneven surfaces can influence horse and rider safety therefore recognizing appropriate techniques to monitor spatial variation and implement relevant maintenance, is of key importance to equestrian athletes.

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Keywords: Equestrian surface; Spatial variation; Functional surface properties; Uniformity; Horse

1. Introduction

Equestrian arenas are designed to produce a surface that supports performance whilst minimising risk of injury during training and competition of sport horses. Uneven racetrack surfaces have been found to place irregular vertical forces on the hoof of racehorses [1] and more recently Murray et al. [2] established that inconsistent arenas increase susceptibility to lameness in dressage horses. It is known that horses modify their gait to compensate for changing surface properties [3,4] however sudden alterations may challenge balance and increase loads on the musculoskeletal system. The relatively passive properties of the distal limb described by McGuigan and Wilson [5] suggest that horses do not adjust limb stiffness when surface properties change, unlike humans whose limb stiffness appears to adapt immediately to variation in surface stiffness [6]. An essential characteristic for optimising arena performance therefore, is spatial uniformity, in order to maintain a regular stride to ensure horse safety and confidence. Intrinsic characteristics such as organic matter, particle size distribution and moisture content [7,8]; percentage fibre

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and morphology [9]; polymer binder [10] and density [11] have all been found to affect the functional properties of a surface. Extrinsic factors including maintenance, installation, specificity and level of traffic, contamination from organic and inorganic substances and age are all relevant to surface behaviour and consistency [12,13]. Spatial variation will therefore be influenced by its physical make-up and the complex interactions between surface constituents and the environment that may amplify surface movement and material breakdown, thus reducing uniformity.

Characterising spatial functional properties of a surface necessitate a standardised, repeatable testing device capable of simulating impact and speed produced during the horse hoof-surface interaction [14]. The benefits of such a testing device mean that data across a surface/s can be directly compared however, the complex interaction between the horse and the surface can never be fully realised using such equipment. A number of surface functional properties including peak load (cushioning) have been described as being relevant to horse performance and health [14]. Peak load gives a measurement of the load carrying capacity of a surface, necessary to support the limb when it is loaded maximally during mid-stance and can influence performance, susceptibility to injury and conditioning of the musculoskeletal tissues [15]. Comparisons between different surfaces has identified too much cushioning can compromise locomotory efficiency and reduce stride length, however surfaces with less cushioning tend to provide performance enhancements [16] and are favoured by riders [17] but may compromise orthopaedic health [15]. Assessing within-surface differences may be difficult for riders, particularly when the visual appearance does not fully reflect the variation in applied loads that the surface can support. As such, a standardised biomechanical testing device and high resolution sampling is expected to be the most effective method of assessing uniformity.

Although uniformity is considered to be an important functional property of equine surfaces, much of the current research has used a low resolution sampling technique, limiting the ability to carry out a detailed analysis of surface variation [18]. The aim of this work was to examine spatial variation of peak load (cushioning) across a synthetic equestrian arena surface and to investigate the influence that physical properties had on these variations by use of multivariate analysis. It was hypothesized that spatial variation of peak load and surface physical properties would be characterised across the arena using Principal Component Analysis (PCA).

2. Materials and methods

2.1 Study design

The project used a well-established indoor equestrian arena that had been laid for two years, measuring 20 m by 65 m. The arena was used moderately for training and competition by 20-50 horses per day and was maintained using a grader (specialized harrow). Harrowing took place regularly and after traffic of approximately 50 horses. The surface was made up of sand, fibre and a polymer binder and was laid to a depth of 150 mm (this varied across the arena). Surface depth and density (mass/volume) were calculated from samples taken in six locations (Figure 1). The arena was divided into a grid of 100 plots, each comprising 1% of the total area. Measurements took place in 61 locations to provide high resolution sampling across the whole arena. The surface was prepared using a grader prior to testing. Testing at every location (*n*=61) occurred in one day using an Orono biomechanical surface tester (OBST) to measure peak load. Temperature and relative humidity were collected using data loggers for 24 hours up to and during testing. Mean ± SD temperature within the surface was 11.53 ± 3.12 ºC; temperature above the surface was 10.99 ± 1.24 ºC and relative humidity above the surface was 88.69 ± 6.66 %. A 200g sample was taken from the point of impact of the OBST at every location and physical properties were analysed in the laboratory.

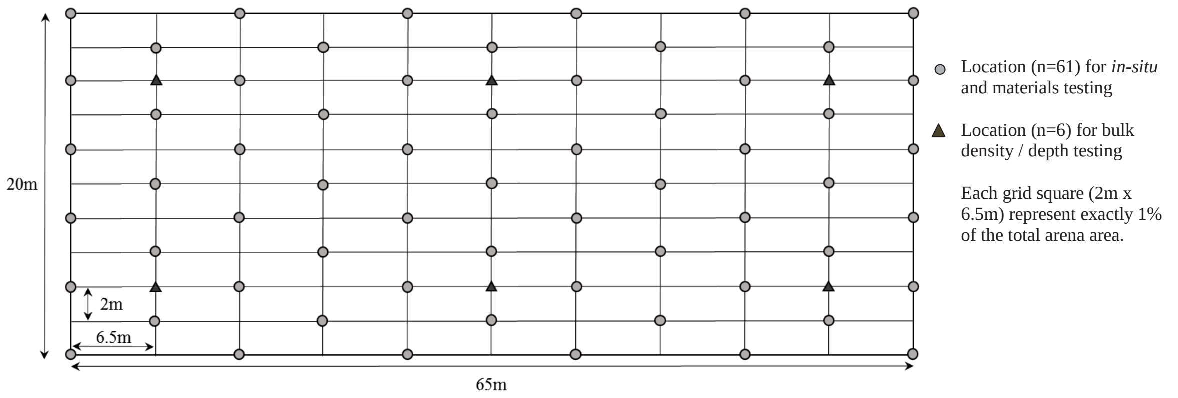

Figure 1. Sample locations used to assess spatial analysis using *in-situ* and laboratory materials testing (n=61) for an equestrian arena surface.

2.2 In-situ testing

The surface testing device used to measure the biomechanical response of the surface (peak load) was the OBST, first described by Peterson et al. [19] and designed to quantify loads experienced by a forelimb impacting the ground in gallop. Peak load was captured from each drop of the OBST at 2000Hz using LabVIEW software. The OBST was dropped twice on the same point to give an indication of the difference between i) a harrowed and ii) a pre-compacted load. Percentage difference between drop 1 and 2 gave an indication of compaction. Files were converted into a suitable ASCII format and imported into Visual 3D where peak load was extracted.

2.3 Laboratory analysis

Samples of 200 g were analysed in the laboratory to provide information about the physical properties of the surface. Moisture content was determined by oven drying each sample at 45 °C for 24 hours and calculating percentage of moisture loss using a modified version of ISO/TS 17892-1:2004. Soxhlet extraction was used to quantify percentage polymer binder and has been described in detail by Bardet and Sanchez [20]. Sieving and weighing was used to establish percentage fibre. Post fibre removal, the particle size distribution (PSD) was identified using ISO 11277:2009(E) by a sieving and sedimentation technique. Percentage organic matter was achieved by burning off organic material using a muffle furnace at 440 ^{0}C using ASTM D2974 (ASTM, 2014). A small number of samples were unable to be tested in the laboratory because of problems during storage. A total of 56 samples provide a complete data set for the analysis (see Table 1 for details).

2.4 Statistical analysis

Normality of all variables was tested using Kolmogorov-Smirnov test ($p \leq 0.05$); moisture content, organic matter and fibre content were identified as non-parametric data. Data were analysed using Minitab 17. Descriptive statistics were calculated for the median and interquartile range. PCA was used to identify main factors that influence surface variations. This generated a series of weighted coefficients which are linear combinations of the original surface data. These principal components provide information on the most meaningful parameters which describe the greatest effects on the data, such that the highest variance by any projection of the data is accounted for in the first axis (PC1), the second greatest variance on the second axis (PC2) and so on. Surface parameters of peak load (kN), moisture content (%), organic matter (%), fibre content (%) and polymer binder (%) were all included in the principle component model. A Spearman's rank correlation was used to assess the relationship between variables from PC1, PC2 and PC3. Hierarchical cluster analysis was applied to identify any evidence of grouping data into categories based on their similarity. The level of similarity diminishes as the group becomes larger and is represented by the Euclidean distance. Cluster analysis established how the changes in physical parameters related to location. Kruskal-Wallis one-way analysis of variance was used to reinforce the findings of the cluster analysis.

3. Results

Descriptive data of all the variables are summarised in Table 1. The surface was characterized by three principal components (PC1, PC2, and PC3) explaining 79% of the total variation in the surface. Peak load and moisture were the first principal components and organic matter and polymer binder were identified as PC2 and PC3 respectively whilst fibre provided some influence for both PC2 and PC3, suggesting their particular individual importance in surface variation. PC1 accounted for 41% of total variance and was correlated with peak load and moisture content. PC2 accounted for 20% of the total variance and was correlated with organic matter and fibre and PC3 accounted for 18% of the total variance and was correlated with polymer binder and fibre. Data for the first two PC axes are presented in Figure 2. There was a significant negative correlation found between peak load drop 1 and moisture (r_s = 54%; P<0.0001) and peak load drop 2 and moisture (r_s = 56%; P<0.0001).

Table 1. Descriptive statistics for peak load drop 1, peak load drop 2, percentage difference between drop 1 and drop 2, moisture content, organic matter, fibre content and polymer binder content. *n*: sample number; IQR: interquartile range

	n	Median	IQR
Peak load Drop 1 (kN)	61	13.79	1.50
Peak load drop 2 (kN)	61	14.49	1.30
Difference between drop 1 and drop 2 (%)	61	7.62	4.45
Moisture content (%)	61	2.38	4.62
Organic matter (%)	56	1.52	1.58
Polymer binder (%)	56	2.31	1.13
Fibre content (%)	57	27.25	11.64
Bulk density (g cm^{-3})	6	1.1	0.15
Surface depth (cm)	6	12.00	3.5

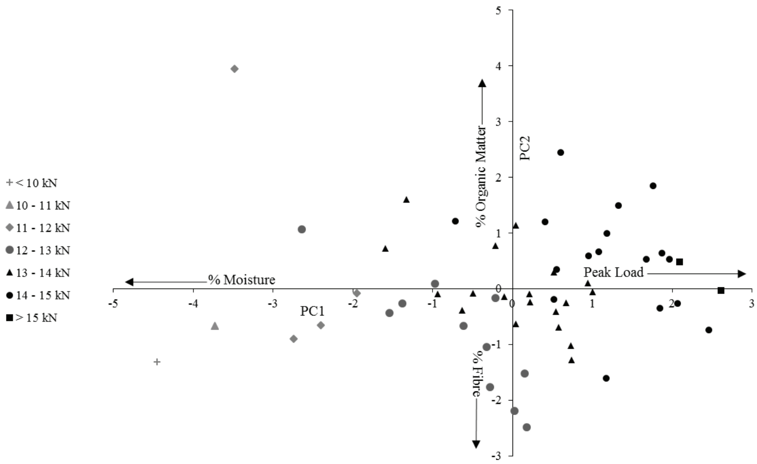

Figure 2. PCA of surface variables along the first two principal components. The first axis was correlated to peak load and moisture content and explained 41% of the surface variation. The second axis was correlated to organic matter and fibre, explaining 20% of the surface variation.

Contour maps provide visual representation of the spatial variation for peak load, moisture content, organic matter and fibre content (Figure 3). Hierarchical cluster analysis revealed peak load and moisture were grouped into five areas of similarity that corresponded to sample location, reinforced using a Kruskal-Wallis ANOVA: $H_{10,61}=37.22$; $P<0.0001$ for peak load drop 1; $H_{10,61}=39.82$; $P<0.0001$ for peak load drop 2 and $H_{10,61}=35.19$; $P<0.0001$ for moisture content .

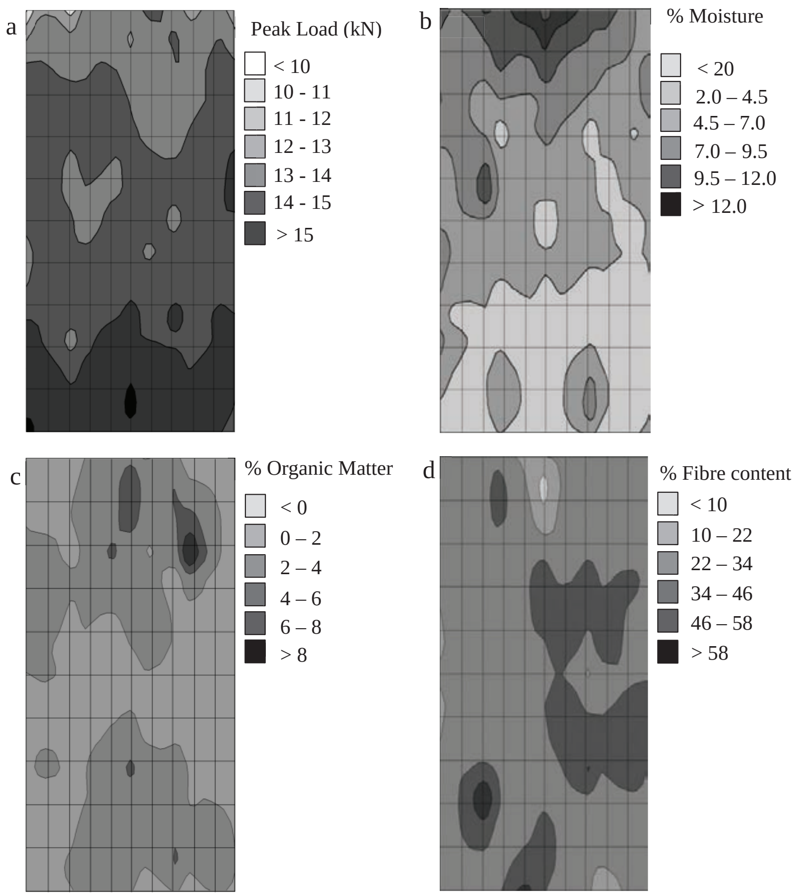

Figure 3. Contour maps of spatial analysis across one equestrian arena surface for a) peak load drop 1 (kN) n=61; b) moisture content (%) n=61; c) organic matter (%) n=56; d) fibre content (%) n=57.

4. Discussion

The key aim of this study was to quantify variation in peak load across an existing two-year-old equestrian arena. Peak load and moisture accounted for the principal variation in the surface and a moderate negative correlation was found. A positive correlation between peak load and moisture (until saturation) has been described by Ratzlaff et al. [8], explained by greater adherence of surface particles and therefore an increased load carrying capacity. The response of the surface will however, be dependent on other factors in addition to moisture. The negative correlation found between peak load and moisture in this study may be due to an increased damping capability [7], resulting in reduced peak loads at high moisture levels. Particle size distribution is relevant to any sand based surface and optimum moisture content will be dependent on the sand profile. Polymer (or wax) coated sand is not considered to be as reliant on watering due to the hydrophobic properties that reduce evaporation and improve drainage rate but this can be dependent on the age of the binder, the surface make-up and environmental conditions [20]. During relevelling the arena tested for this study was heavily watered at 12 monthly intervals but no additional water was applied during the intervening periods. Moisture content in polymer coated surfaces, should provide limited influence on the biomechanical response of the surface (particularly shear strength), because of these hydrophobic properties [21]. The findings in this current study suggest that moisture content is a significant factor. Spatial variation of moisture was identified in specific areas of the arena which may be due to environmental factors such as drainage related to the type of base layer, possible leaks in the roof and temperature. Murray et al. [12] described crushed concrete base layers as less favourable because of a lack of stability and susceptibility to drain blockage. The arena in this current study was installed on a crushed concrete base layer and this may have been a reason for evidence of areas with higher levels of water. Other reasons for this variation may be fibre morphology, polymer binder degradation [20] and particle size distribution. Particle size distribution was found to be relatively homogenous however it can influence compaction of sand [22], bulk density and porosity and therefore water holding capacity. Additionally, sand morphology (grain angularity) is a significant factor on how well a surface drains [23], which was not analysed here. There is limited knowledge about how polymer binders degrade over time. Soxhlet extraction has been used to separate the binder from the rest of the surface but this technique does not produce any specific detail about binder composition. It is likely that polymer binders will alter over time due to a number of factors such as surface maintenance, climate and inorganic and organic pollutants in the surface. Polymer binders for equestrian surfaces are normally made up of a paraffin wax-oil blend and microcrystalline wax [10]. Gas chromatography and differential scanning calorimetry have been used to characterize the wax coating of synthetic surfaces in order to understand more about its behavior during changes in temperature [10], this technique would be a useful tool to assess changes to polymer binders over time that may alter behavior and uniformity of a surface.

Peak load was generally lowest at drop 1 and SDs for both drop 1 and drop 2 were small which is broadly comparable to Tranquille et al. [18] who described low SDs on a harrowed, wax-coated surface. Differences between drop 1 and drop 2 can indicate how much compaction occurs, due to plastic deformation when a horse lands on it. There was a relatively small difference between drop 1 and drop 2 suggesting that peak load was quite consistent between a horse working on a newly harrowed surface (drop 1) and a horse working on a pre-compacted surface (drop 2), this finding supports Murray et al. [12] who suggested that wax coated surfaces appear to tolerate high use between maintenance. Peak load is a measure of the stiffness and damping characteristics of a surface and is influenced by both plastic and elastic properties, therefore it is an appropriate measurement to assess compaction of a surface. It is important to note that measuring impact firmness, responsiveness and grip capability is also relevant to considering surface compaction. Additives such as fibre can be beneficial in reducing compaction by improving elastic properties, increasing shear strength by providing stability and optimizing drainage [9,20]. Percentage fibre demonstrated some variation across the surface however this was not one of the key parameters relevant to differences and this may be partly due to the surface only being two years old. Fibre particles would be susceptible to degradation over time, particularly in a surface containing organic matter (as was evident in this specific arena). Synthetic fibres, as used in this particular study are less vulnerable to degradation, however it is important that organic matter such as horse faecal material is continually removed from the surface. Fibre size, shape and type were visually heterogeneous (but were not quantified) and therefore some overall variation would be expected. Further understanding about how fibre morphology and homogeneity influences biomechanical responses such as shear resistance and responsiveness, would provide more comprehensive conclusions. Organic matter has been reported in previous literature [7] as a method of classifying wood content (i.e. woodchip surfaces) whereas organic matter in this current study was made up of biological material such as faecal matter, bedding, hair and skin. The relationship between the break-down of fibre and organic matter as discussed above, may be of most relevance here.

Density and surface depth was calculated in six locations of the arena and there was evidence of some variation. Mahaffey et al. [24] reported that a difference of 50 mm in cushion depth significantly altered the peak load; differences between the six locations identified in this arena demonstrated a difference of 50 mm surface depth that may therefore influence peak load. Unfortunately surface depth was taken from six locations not directly related to the peak load data. It is recommended that future assessment of uniformity should include measurement of surface depth to provide a more comprehensive profile. Inconsistent surface depth has been described as altering gait and locomotory efficiency and therefore poses a risk to lameness [25], additionally, surfaces that are uneven can initiate trips and loss of balance. The horse is considered to have limited capability to accommodate changes in surface properties, due the relatively passive structures present in the distal limb [5]. Postural modifications are likely to assist in these circumstances [4], however adaptation stride to stride on an uneven surface is unlikely [22], although this depends on magnitude and frequency of irregularities. There is a need to develop greater understanding of the biomechanical responses to uneven surface conditions, additionally, it is expected that rider evaluation will play an important part in determining what constitutes unacceptable unevenness in the future.

The use of PCA and contour maps has been found to be a useful method for spatial analysis of equestrian surfaces using a high resolution sampling technique. Uniformity is a key aspect of surface assessment and is expected to have significant effects on horse safety and performance, although this has not been measured here. Some of the physical properties of the surface may not influence peak load but will be relevant to other biomechanical responses and must be considered in light of these findings, this study is limited to the methods used to assess the surface. A comprehensive understanding of how spatial variation affects the horse, would need to consider other functional properties that include impact firmness, grip and responsiveness as described by Hobbs et al. [14]. A surface may appear to be homogenous but subtle differences in surface condition should be corrected by arena managers to reduce risk of injury. It is suggested that in addition to regular maintenance, assessment of spatial differences will allow targeted remedial work in order to improve uniformity and optimise surface function.

5. Conclusion

Key factors influencing spatial variation in this specific surface are peak load and moisture content which are inversely correlated. Moisture content is known to be a significant characteristic that affects the biomechanical response of a surface and it is suggested that higher moisture levels can influence damping and therefore, peak loads. The use of multivariate analysis and contour maps demonstrate an effective method of assessing arena uniformity and identifying physical factors relevant to the load carrying capacity of this specific surface. Recognising appropriate techniques to monitor spatial variation and implement relevant maintenance, is of key importance to support horse performance and health.

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