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The Development of a Standardized Protocol for Quantifying Equestrian Eventing Cross-Country Ground

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Abstract: The ground has long been cited as a key contributing factor for injury risk in the cross-country phase of eventing. The current study aimed to develop a practically useful standardized protocol for measuring eventing cross country ground. Data collection was split into three phases: Phase 1 (Validation), Phase 2 (Expansion of data set), and Phase 3 (Threshold establishment). During Phase 1, data from nine event courses were collected using an Orono Biomechanical Surface Tester (OBST), Vienna Surface Tester (VST), Lang Penetrometer, Going Stick, and moisture meter. Using linear regression, 80% of the variability in cushioning measured with the OBST was predicted from moisture and VST measurements ($p < 0.001$). In Phase 2, objective data from 81 event courses and subjective assessments from 180 event riders were collected. In Phase 3, k-means cluster analysis was used to classify the courses into ten clusters based on average course measurements of moisture, cushioning, firmness, stiffness, depth, and coefficient of restitution. Based on cluster membership, course average subjective data (16 courses) were compared using a General Linear Model. Significant differences ($p < 0.05$) in subjective impact firmness ($p = 0.038$) and subjective cushioning ($p = 0.010$) were found between clusters. These data and cluster thresholds provide an event course baseline for future comparisons.

Keywords: turf; surface measurement; equine; injury risk; eventing; soil; moisture; cushioning; surface stiffness; firmness

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1. Introduction

The cross-country phase is one of three equestrian disciplines that make up eventing competitions, and has been identified as the discipline that carries the greatest risk of injury to both horse and rider [1]. Since the year 2000 there have been at least 50 reported human deaths and 109 reported horse deaths from injuries sustained during the cross-country phase of eventing at both the national and international levels [1]. Injury in the cross-country phase has most frequently occurred due to a horse fall at a cross-country fence. In 2020, over 80% of horse falls were at a cross-country fence in international competitions, and a higher number of falls were reported in the long format compared to the short format [2]. Long format competitions usually take place over three days, have a longer cross-country course with more jumping efforts, and usually involve cross-country preceding show jumping. Short format competitions take place over one or more days, the cross-country course is shorter, and it is usually the last discipline.

In addition to the risk of fatal injuries, a high frequency of withdrawals due to non-fatal musculoskeletal injuries has historically been reported. For example, horse withdrawals due to non-fatal locomotor injuries reported by the Netherlands team during preparation for European Championship competition in 2010–2011 made up 45% of all injuries [3]. In another study, 35.1% of UK horses that were registered with British Eventing in 1999 were not re-registered the following year due to veterinary problems [4]. While course-related factors, including level and distance, were identified as risks for horse falls [1], the accumulation of mechanical stress cycles prior to, during, and following competition was expected to impact horse tissue health, potentially leading to either positive adaptation or pathological changes [5,6]. Additional course-related risk factors that were likely to influence the magnitude of the forces at the ground and consequent levels of mechanical stress that the horse would experience include surface, fence size, speed, and course complexity [7], all of which can be modified to a greater or lesser extent.

The functional properties and characteristics of equine competition surfaces that could contribute to injury risk were summarized by Hobbs et al. [5], who illustrated how these properties may influence limb loading and resultant magnitudes of mechanical stress. Although these properties and characteristics can be measured 'independently' by different pieces of equipment, or indeed by horses, the work cited above described how surface measurements depend on and influence each other.

Historically, equine turf surfaces have been categorized using various subjective and objective measures ranging from walking sticks to going sticks [8]. These methods have often been lacking in both adherence and standardization, resulting in variability in the categorization of surfaces by different groundskeepers at different venues. In 2008, Peterson and colleagues designed an instrumented device that could replicate limb loading at gallop [9], which was later named the Orono Biomechanical Surface Tester (OBST). The OBST has been extensively used on racetracks in the United States [10] and equestrian arenas worldwide [11,12], and has been adopted by the Fédération Equestre Internationale (FEI) as a gold standard measurement tool for quantifying show jumping surfaces at international events [5]. Five surface functional properties are measured using the OBST, namely, impact firmness, cushioning, responsiveness, grip, and uniformity [5–11]. This equipment was used at both the Rio de Janeiro and Tokyo Olympics to measure the cross-country ground prior to events; however, it is usually maneuvered around the course with a vehicle. As cross-country courses follow natural terrain over several kilometers and can be challenging to negotiate, this discipline would benefit from a measurement tool that can measure surface functional properties while being more practical to use in cross-country settings.

Several pieces of equipment exist which have the potential to replicate measures obtained by the OBST while being smaller and easier to manage when transported around a cross-country course. Additionally, no standardized protocols currently exist for quantifying cross-country ground using the OBST or other equipment. Therefore, the aims of this study were to: (1) develop a standardized protocol for measuring eventing cross country ground; (2) evaluate a range of surface testing equipment for suitability in measuring eventing cross country ground compared to the gold standard OBST; and (3) develop a database of functional properties and subjective measurements that can be used to establish threshold ranges for classification of eventing cross-country ground.

Our hypotheses were as follows: (1) there would be a strong relationship between the moisture and surface functional properties measured with the OBST; (2) equipment that was designed to measure similar constructs to the OBST would strongly predict surface functional properties; and (3) impact firmness would be more readily perceived by event riders than other surface functional properties [5,11,13–15].

2. Materials and Methods

The data collection process was broken down into three distinct phases: Phase 1 (Validation), in which a range of equipment was tested against the OBST to ascertain which equipment would be used in Phase 2; Phase 2 (Expansion of the Dataset), where objective and subjective data were collected from a range of different events and courses using the validated test equipment; and Phase 3 (Threshold Establishment), in which the dataset of measures for cross-country ground was compiled and initial thresholds for cross-country ground were established. The procedures, data processing, and statistical analysis for each phase are each defined in their own subsections of the Methodology Section.

Ethical approval was obtained from Nottingham Trent University (ARE202133) and the University of Central Lancashire (HEALTH 0188). Informed consent was obtained from the riders to collect subjective data.

2.1. Cross-Country Courses

A total of 98 cross-country event courses were tested between 2019–2022 during the eventing season, which runs from March to September in the UK each year. The event courses were all turf, some had crossing tracks, and most had prepared ground around fences. The turf galloping track of each event course was tested in the afternoon on the day before cross-country day. These included fifteen British Eventing intermediate courses (BEInt), four British Eventing advanced courses (BEAdv), thirteen British Eventing novice courses (BENov), sixteen British Eventing 100 courses (BE100), three British Eventing 90 courses (BE90), one British Eventing 80 course (BE80), three FEI 5* long courses (FEI5*L), seven FEI 4* long (FEI4*L) and seven FEI 4* short courses (FEI4*S), six FEI 3* long (FEI3*L) and three FEI 3* short courses (FEI3*S), one FEI 2* short course (FEI2*S), sixteen Unaffiliated 100 courses (UA100), two Unaffiliated 90 courses (UA90), and one training course.

2.2. Equipment

2.2.1. Orono Biomechanical Surface Tester v2 (OBST)

The OBST (custom-made by the Swedish University of Agricultural Sciences, Uppsala, Sweden) is a mechanical device designed to imitate the impact of a horse's forelimb during gallop when in contact with a surface [9,11]. The device is designed to drop a horseshoe-shaped metal plate affixed to a metal mount onto a surface from a height of 84 cm at a set incline from the vertical axis. Measurements of the impact are obtained via two linear potentiometers, one measuring drop speed and one measuring spring displacement, two single axis load cells, one measuring vertical load and one measuring horizontal load, and two single axis accelerometers, one measuring vertical acceleration and one measuring horizontal acceleration. Nine channels of data were obtained with 16-bit resolution at 5000 Hz via the MATLAB environment (v2018a, The MathWorks, Inc., Natick, MA, USA) and used to calculate the five functional properties: impact firmness, cushioning, responsiveness, grip, and uniformity [11].

The following test equipment was selected based on transportability around a cross-country course and potential to correlate with the different measurements obtained by the OBST. A summary of the equipment, the number of measurements used for each location, the measurements, and the units used in the study are described in Table 1.

Table 1. Summary of equipment, measurements, and units used in the study.

Equipment	Number of Measurements/Location	Measurement Name	Measurement	Units
Orono Biomechanical Surface Tester (OBST)	1	Impact Firmness	Peak vertical acceleration	g
		Cushioning	Peak vertical force	kN
		Responsiveness	Ratio of head compression and recoil timing	ratio
		Grip	Derived horizontal displacement	mm

Table 1. *Cont.*

Equipment	Number of Measurements/Location	Measurement Name	Measurement	Units
Vienna Surface Tester (VST)	14+	Gmax	Peak impact acceleration	g
		Depth	Derived penetration depth	mm
		ER	Coefficient of restitution	%
		k	Stiffness	kN/m
Lang Penetrometer	5	Compaction	Penetration resistance	MPa
Going Stick	3	Going value	Penetration and Shear resistance	Index (N and Nm)
Moisture Meter	5	Moisture	Volumetric water content	%

2.2.2. Vienna Surface Tester (VST)

The VST [16], developed, patented, and manufactured by Veterinary University Vienna, Vienna, Austria, is a 20.4 cm diameter 6.15 kg weighted ball containing two accelerometers (250 g and 2 g). The signal of the 250 g accelerometer is processed with a Bessel-type low-pass filter of 400 Hz for noise reduction and sampled with 10 kHz for peak detection. The 2 g accelerometer serves as a free-falling (zero-g) detector [17]. To obtain measures, the VST is repeatedly dropped across a section of turf at least fourteen times from gradually increasing random drop heights ranging from 0.05 m to 0.85 m, which allows for collection of differing impact velocities in the range between 1 m/s and 4 m/s. Affixed to the top of the weighted ball is a data acquisition box used to obtain data during two impacts between the bouncing ball and the ground. The accelerometers are used to measure the free-fall time and impact acceleration. The measured and calculated data collected were impact velocity, impact acceleration (Gmax), penetration depth (Depth), coefficient of restitution (ER), and stiffness (k), which were stored as a CSV file on a microSD card, which was then transferred to a laptop and input to an Excel spreadsheet. Linear regression was performed in Microsoft Excel (v2304, Microsoft Corp., Overlake, Redmond, WA, USA) to provide a predicted value for each measurement at 2 m/s and 4 m/s for comparison of the ground at different depths [17]. For each measurement, either a 2 or a 4 follows the measurement to distinguish between the different speeds.

2.2.3. Lang Penetrometer

The Lang penetrometer (Lang Penetrometer Inc., Gulf Shores, AL, USA) is a small handheld spring-loaded device used to measure the compaction of soil. Data are obtained by pushing the thick needle end of the device into the turf; the device can measure soil compaction from 0 to 4.35 MPa. Data from the Lang Penetrometer were manually collected by reading the compaction measurement from the side of the device and recorded on a paper data sheet. Five measurements were taken, and the mean value was recorded at each location.

2.2.4. Going Stick

The Going Stick (TurfTrax Ltd., Cambridgeshire, UK) is a penetration and shear resistance testing device, similar in size and appearance to a walking stick with a handle. It has a 100 mm long flat steel tip that is first pushed into the ground to measure penetration resistance and then pulled back to an angle of 45 degrees to measure shear resistance [8]. Strain gauges are used to measure resistance and the data are combined into one going value. The Going Stick reports a single value, which is an average of three measurements.

2.2.5. Moisture Meter

The Delta-T HH2 moisture meter (Delta-T Devices Ltd., Cambridge, UK) is a small handheld device which is attached to a Theta Probe ML3 by a short wire. The probe has

60 mm rods that are inserted into the ground. Soil moisture was measured using the default mineral soil setting, measured as % volumetric water content. Five measurements were taken and the mean value was recorded at each location.

2.3. Phase 1: Validation

2.3.1. Protocol Development

Pilot data were collected from five cross-country courses (BENov-BE100) using the OBST, the moisture meter, and the Lang Penetrometer to establish a sampling method that would efficiently characterize a cross-country course for a competition. Data were collected from each course at 125 m intervals from the start to the finish. At each 125 m location, measurements were taken using each piece of test equipment in an area of approximately 1.5 m by 1.5 m. To minimize the risk of compaction influencing the results, the test location for each piece of equipment and each repetition was as close as feasibly possible without being directly on top of a previous measurement. For the penetrometer and moisture meter, visual inspection of the ground was undertaken before data was collected to ensure that any spiked holes left during ground preparation were avoided.

All the measurements from each piece of equipment were matched by location and compiled into separate headed columns in Excel. The coefficient of variation (%COV) was calculated for each course and each measurement. The %COVs were then compared between 125 m and 250 m intervals (i.e., data were removed from 125 m, 375 m, etc.) to establish whether sampling at 250 m would effectively characterize the cross-country course using an F-Test [18]. Data analysis was conducted using SPSS (v28.0, SPSS Inc., Chicago, IL, USA). Significance was set to $p < 0.05$.

The results of the comparison between taking measurements at 125 m and 250 m locations demonstrated no significant difference in variation across the course. Table 2 provides a summary of these results.

Table 2. Means and standard deviations for the coefficient of variation (%COV) for five event courses when measurements were compared at 125 m and 250 m locations. N, number of courses measured (data were missing for grip measurements from three courses). OBST measurements: Impact firmness, cushioning, responsiveness, grip. Lang Penetrometer measurement: compaction. Significance was set to $p < 0.05$.

	Measurement	N	125 m	250 m	F-Value	*p*-Value
Mean	Impact Firmness	5	26.57	26.99	1.378	0.761
	Cushioning	5	15.25	15.84	1.526	0.692
	Responsiveness	5	56.03	51.47	0.995	0.997
	Grip	2	12.86	9.47	2.302	0.606
	Moisture	5	24.91	24.78	0.644	0.680
	Compaction	5	12.29	11.99	1.852	0.565
Standard Deviation	Impact Firmness	5	9.27	11.27	1.477	0.715
	Cushioning	5	5.99	7.96	1.761	0.597
	Responsiveness	5	32.29	29.57	1.192	0.869
	Grip	2	2.80	3.77	1.816	0.813
	Moisture	5	6.35	5.02	1.600	0.660
	Compaction	5	4.19	5.79	1.913	0.545

2.3.2. Evaluation of Test Equipment

Data from nine event courses (FEI 5* long–training course) were collected with the full range of available equipment (OBST, VST, Lang Penetrometer, Going Stick, and moisture meter). Data were collected at 250 m intervals and processed using the methods described in Sections 2.2 and 2.3.1.

2.3.3. Statistical Analysis

The relationships between functional properties produced from the OBST were compared to each piece of test equipment using Pearson's Correlation. Where significant, a very strong relationship was denoted by a correlation coefficient (r) of ≥0.8, a strong relationship by r = 0.6–0.79, a moderate relationship by r = 0.4–0.59, and a weak relationship by r = 0.2–0.39. For each OBST functional variable (dependent variable), forward linear regression was used to establish which measurements from the moisture meter, Lang Penetrometer, and VST (independent variables) predicted the functional surface properties measured by the OBST. Data analysis was conducted using SPSS (v28.0, SPSS Inc., Chicago, IL, USA). Significance was set to $p < 0.05$.

2.4. Phase 2: Expansion of the Dataset

2.4.1. Procedures

Over the 2021–2022 eventing seasons, functional surface properties were collected every 250 m using the moisture meter, Lang Penetrometer, and the VST from 81 event courses, ranging from 5* long to unaffiliated 100 courses, and processed using the methods described in Sections 2.2 and 2.3.1 and File S1. Predicted functional properties were calculated from the regression analyses in Phase 1. The Lang Penetrometer was only used during the 2021 eventing season.

Subjective evaluation of the functional properties of cross-country ground (impact firmness, cushioning, responsiveness, grip, uniformity) together with an overall rating (Table S1 was collected from a group of 180 event riders competing at 18 of the 81 events (15 ± 9 responses/event). The profile of the event rider group is provided in Table 3.

Table 3. Profile of the event riders that participated in the study (n = 180). Abbreviations: Minimum entry requirements (MER), Fédération Equestre Internationale (FEI), Concours Complet International (CCI).

FEI Rider Grade	Number of Riders	Number of Responses	Responded at 2 or More Events
A	45	74	20
B	59	82	15
C	56	75	14
D	15	21	4
NC	5	5	0

D = Ten (10) MER at FEI CCI short (CCIs-S) or long (CCIs-L) format competitions of two-star level or above, or three (3) MERs at FEI CCI short (CCIs-S) or long (CCIs-L) format competitions at higher level. C = Ten (10) MER at FEI CCI short (CCIs-S) or long (CCIs-L) format competitions of three-star level or above, or three (3) MERs at FEI CCI short (CCIs-S) or long (CCIs-L) format competitions at higher level. B = Ten (10) MER at FEI CCI short (CCIs-S) or long (CCIs-L) format competitions of four-star level or above, or three (3) MERs at FEI long format (CCIs-L) competitions at five-star level. A = Ten (10) MER at FEI CCI short (CCIs-S) or long (CCIs-L) format competitions of four-star level or above, of which three (3) were at five-star level. NC means that not enough events were completed to obtain an initial D category.

Rider evaluations were completed within 20 min of completing the cross-country course while the experience was still fresh in their mind. Prior to the commencement of the 2021 eventing season, riders were invited to voluntarily take part in the study. To ensure familiarity with the terminology, the research team prepared a presentation which provided details about the study and explained the functional surface properties in more detail. The presentation was videoed and uploaded to YouTube. Riders that volunteered were given access to the presentation via a private link and were sent a one-page document explaining the surface functional properties. Additional riders who volunteered to take part at events were provided with an explanation of the study and surface functional properties by one of the researchers. Data were collected using a questionnaire adapted from [11], using a visual analogue scale to evaluate the surface functional properties (Table S1).

2.4.2. Data Compilation

Objective evaluation of cross-country ground was compiled into an individual event report format for each event. The report was produced on-site by the research team once the measurements had been collected and was sent directly to the event organizers. The report was not made publicly available. The report contained measurements from the moisture meter and the VST. Predicted cushioning (PC) was calculated using the regressions equations developed from Phase 1 for each location where Gmax4 is impact acceleration at 4 m/s and ER4 is the coefficient of restitution at 4 m/s.

$$\text{Predicted Cushioning (PC)} = \text{Gmax4} \times 0.079 + \text{Moisture} \times (-0.028) + \text{ER4} \times 0.104 + 3.468 \quad (1)$$

To assist the event organizers in interpreting the data, a color coding system was established that defined the threshold ranges related to turf going for each measurement. Typical descriptions related to turf were used to assist the event organizers in understanding the threshold ranges (soft, good to soft, good, good to firm, firm, hard). For moisture, ER and course variability descriptions and ranges were developed that were applicable to the measurements. Thresholds were developed over the time course of the project using an iterative learning process. The outcomes of the competition, feedback from subjective evaluations, and additional verbal feedback from riders and organizers were reviewed against the measurements produced by the research team after each event. Small revisions were made when the consensus across multiple events did not match the current thresholds.

The mean, standard deviation, and %COV were determined for each measurement included in the report. The average %COV was calculated to provide an overall course variability factor as a measure of uniformity.

2.5. Phase 3: Threshold Establishment

Average course measurements from the 81 courses were compiled to evaluate the thresholds that were iteratively established for the report in Phase 2.

Statistical Analysis

K-means clustering analysis was used to classify the 81 event courses into ten clusters in order to evaluate the use of a 0–10 scale to classify going for eventing cross-country courses. Clusters were classified using course average measurements that were included in the report (moisture, predicted cushioning, impact acceleration at 4 m/s (Gmax4), penetration depth at 4 m/s (Depth4), coefficient of restitution at 4 m/s (ER4), and stiffness at 2 m/s and 4 m/s (k2 and k4)). Cluster membership for each event course was saved. Event course average subjective functional properties (impact firmness, cushioning, responsiveness, and grip) were arranged using the cluster membership from objective classification and analyzed using a General Linear Model and Bonferroni post hoc testing to evaluate differences between clusters. In addition, relationships between course average measurements that were included in the report and subjective functional properties were explored using Pearson correlations. Data analysis was conducted using SPSS. Significance was set to $p < 0.05$.

Descriptive statistics of the range of data for objective and subjective measurements for all event courses within each cluster were compiled in Excel.

3. Results

3.1. Phase 1: Validation

The range of data (min to max) recorded from nine cross-country courses with the OBST and other equipment were: moisture = 10 to 63%, OBST impact firmness = 13 to 151 g, cushioning = 5 to 16 kN, responsiveness = 0.68 to 1.69, grip = 0.09 to 0.21 m, Lang penetrometer compaction = 6 to 16.5, Going Stick = 5.87 to 11.9, VST impact acceleration at 2 m/s (Gmax2) = 22 to 70 g, Gmax4 = 52 to 157 g, penetration depth at 2 m/s (Depth2) = 7 to 29 mm, Depth4 = 13 to 37 mm, ER2 = 6 to 23%, ER4 = 4 to 17%, k2 = 86 to 786 kN/m, k4 = 101 to 914 kN/m.

Table 4 displays the Pearson correlation coefficients between the key parameters used to define surface going obtained by the OBST (impact firmness, cushioning, responsiveness, and grip) compared against each piece of equipment selected to be used in place of the OBST. All measures obtained from the moisture meter, Lang penetrometer, and Going Stick were significantly correlated (≤0.01) with impact firmness, cushioning, responsiveness, and grip. The range of correlations were from weak to strong for moisture and compaction and from moderate to strong for the Going Stick. All measures obtained from the VST significantly correlated (≤0.01) with impact firmness, cushioning, and grip obtained from the OBST, ranging from weak to very strong correlations. The only measures that did not significantly correlate ($p > 0.05$) were ER at 2 m/s obtained from the VST and responsiveness obtained from the OBST (Table 4). For all equipment and measures except for ER, the strongest relationships were found with OBST cushioning, with the strongest being Gmax at 4 m/s (r = 0.876, $p < 0.01$).

Table 4. Pearson correlation coefficients comparing the functional properties obtained from the OBST (impact firmness, cushioning, responsiveness, and grip) against the data obtained from the moisture meter (moisture), Lang penetrometer (compaction), Going Stick, and Vienna Surface Tester (impact acceleration (Gmax), penetration depth (Depth), coefficient of restitution (ER), and stiffness (k) at 2 m/s and 4 m/s)). Note: data from the Going Stick were only available from three courses due to operational issues.

OBST	Moisture	Compaction	Going Stick	Vienna Surface Tester Measurements (at 2 and 4 m/s)							
				Gmax2	Gmax4	Depth2	Depth4	ER2	ER4	k2	k4
Impact Firmness	−0.312 **	0.473 **	0.449 **	0.532 **	0.588 **	−0.438 **	−0.559 **	−0.508 **	−0.571 **	0.583 **	0.639 **
Cushioning	−0.746 **	0.788 **	0.661 **	0.739 **	0.876 **	−0.596 **	−0.784 **	−0.256 **	−0.208 *	0.751 **	0.857 **
Responsiveness	0.416 **	−0.365 **	−0.592 **	−0.426 **	−0.471 **	0.290 **	0.424 **	00.152	0.199 *	−0.447 **	−0.455 **
Grip	−0.305 **	0.544 **	0.422 **	0.625 **	0.694 **	−0.572 **	−0.543 **	−0.537 **	−0.581 **	0.673 **	0.738 **

** Correlation is significant at the 0.01 level (two-tailed). * Correlation is significant at the 0.05 level (two-tailed).

The results of forward linear regression are shown in Table 5. The variability in OBST functional properties could be predicted by moisture, VST measurements at 4 m/s, and compaction. From these data, it is evident that 80% of the variance in cushioning measured by the OBST can be predicted by the VST measures of Gmax4 and ER4 together with moisture. An illustration of this relationship for each measurement is shown in Figure 1. Conversely, only 21% of the variation in OBST responsiveness could be predicted by other equipment.

3.2. Phase 2: Expansion of the Data Set

Descriptive data from the 2021 and 2022 eventing seasons are illustrated in Figure 2, separated by course level groupings. Groupings were as follows: 80-Nov (forty courses), Int (thirteen courses), Adv-FEI2* (five courses), FEI3* (eight courses), FEI4* (thirteen courses), and FEI5* (two courses).

An example of an anonymized datasheet providing the most current threshold ranges is shown in Figure S6 in File S1. The protocol for testing eventing cross-country ground is described in File S2.

The number of responses from the eighteen event courses for which subjective data were collected varied due to rider availability at the end of the cross-country course. Figure 3 illustrates the responses for subjective cushioning by event course. Two event courses were identified as unreliable due to a very small number of respondents for one and heavy rainfall following data collection and before the start of cross-country for the other. These were removed from the dataset prior to the evaluation of thresholds.

Table 5. Results of the forward linear regression show the significant predictors of functional surface properties using measurements from the moisture meter, Lang penetrometer, and VST. Impact acceleration (Gmax), penetration depth (Depth), coefficient of restitution (ER), and stiffness (k) at 4 m/s.

		F	R^2	*p*	Significant Predictors
OBST Functional properties	Impact Firmness	37.753	64.9%	<0.001	k4 ER4 Gmax4 Depth4 Compaction
	Cushioning	139.089	80.0%	<0.001	Gmax4 Moisture ER4
	Responsiveness	28.221	21.0%	<0.001	Gmax4
	Grip	43.455	68.8%	<0.001	k4 Gmax4 ER4 Moisture

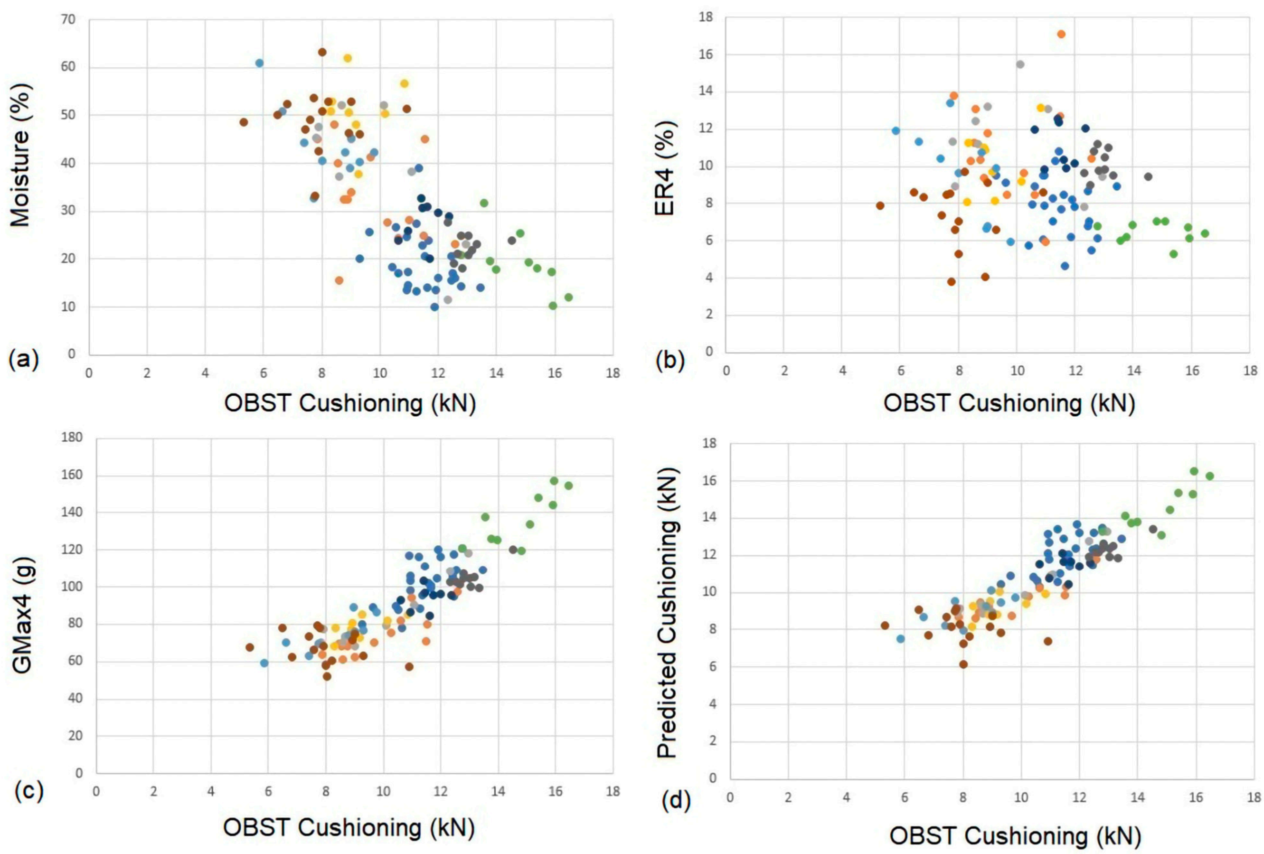

Figure 1. Illustration of the measurements used to predict cushioning against cushioning measured with the OBST from the nine event courses used in Phase 1. Each event course is identified by a different color. (**a**) Relationship between moisture (%) and OBST cushioning (kN), (**b**) relationship between coefficient of restitution at 4 m/s (ER4) (%) and OBST cushioning (kN), (**c**) relationship between impact acceleration at 4 m/s (Gmax4) (g) and OBST cushioning (kN), (**d**) relationship between predicted cushioning using the regression equation (kN) and OBST cushioning (kN).

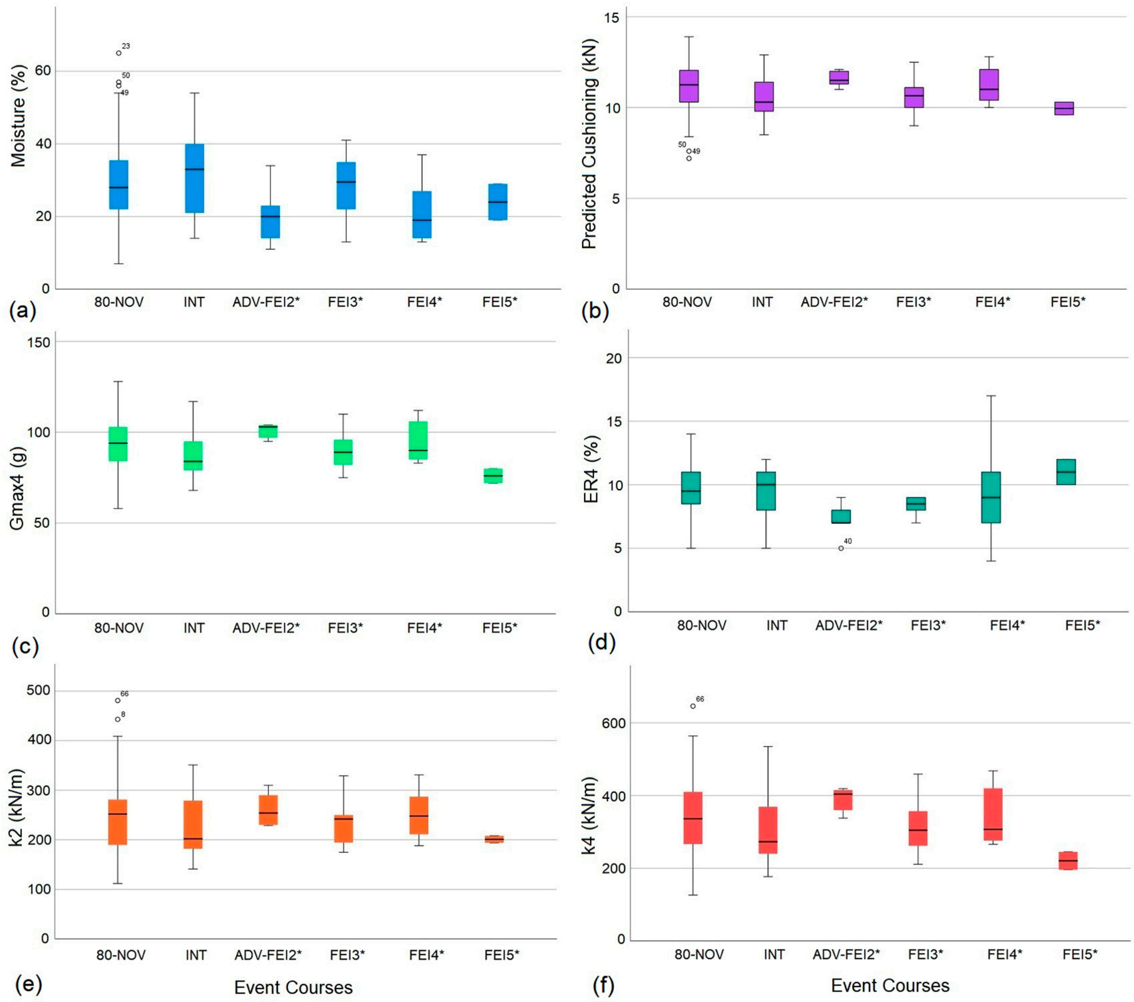

Figure 2. Boxplots of data from 2021 and 2022 eventing season (81 event courses) showing data for (**a**) moisture (%), (**b**) predicted cushioning (kN), (**c**) impact acceleration at 4 m/s (Gmax4) (g), (**d**) coefficient of restitution at 4 m/s (ER4) (%), (**e**) stiffness at 2 m/s (k2) (kN/m), and (**f**) stiffness at 4 m/s (k4) (kN/m) separated by course levels. Abbreviations: Novice (NOV), Intermediate (INT), Advanced (ADV), Fédération Equestre Internationale (FEI).

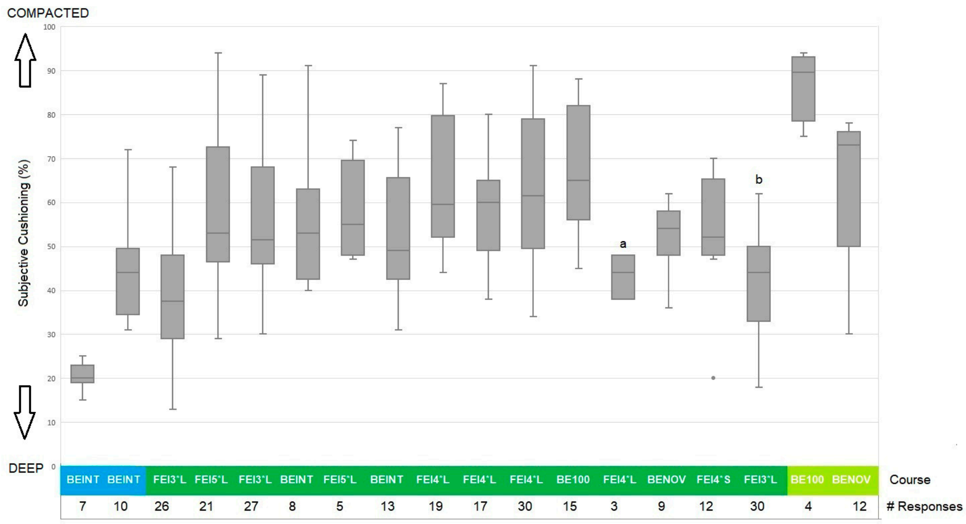

Figure 3. Subjective cushioning assessments of eighteen event courses ordered by event course threshold bandings used in the report. Two courses were identified as unreliable due to a: a very small

number of respondents and b: heavy rainfall following data collection and before the start of cross-country as it is shown in the figure. Abbreviations for course classification: British Eventing Intermediate (BEINT), Fédération Equestre Internationale 3*, 4*, 5* Long (FEI3*L, FEI4*L, FEI5*L), Fédération Equestre Internationale 4* Short (FEI4*S), British Eventing Novice (BENOV), British Eventing 100 (BE100).

3.3. Phase 3: Threshold Development

The results of the k-means clustering analysis using the course average objective measurements to classify event courses into ten clusters are shown in Figure 4. Clusters converged in six iterations. The final cluster center distances are plotted against the distance of each event course from its classified cluster center. The plot shows a small cluster separation between clusters 2 to 4 and 5 to 6, with a large cluster separation between the other clusters.

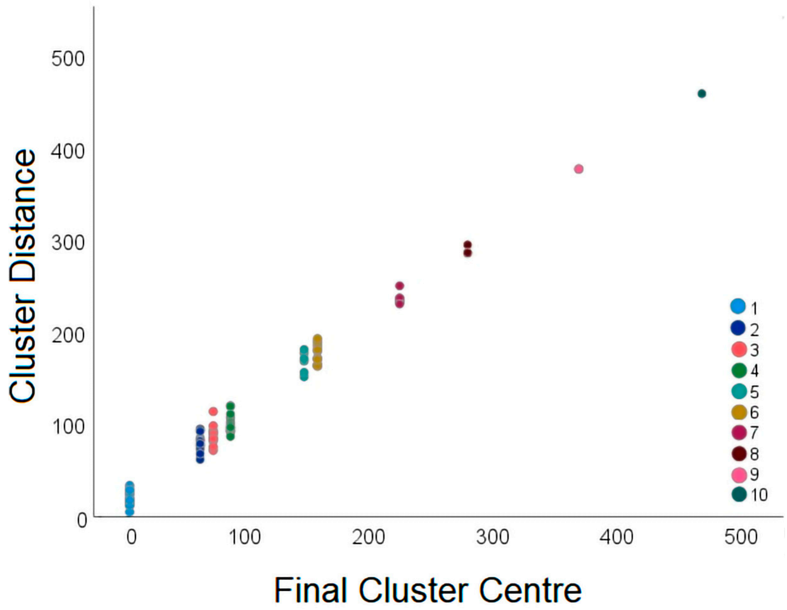

Figure 4. Results of k-means clustering analysis of objective data used to separate the 81 event courses into 10 clusters. The final cluster center distance is plotted on the *x*-axis against the distance of each event course to its classified cluster center on the *y*-axis. Clusters (n = 10) are differentiated by color.

The range of measurements for each cluster are shown in Figure 5 together with the number of event courses that were classified in that cluster, the type of event, and the colored threshold bandings. Most event courses (50 event courses, 62%) were represented by four clusters. These clusters had a range of predicted cushioning = 8.9 to 12 kN, Gmax4 = 72 to 101 g, k2 = 163 to 280 kN/m and k4 = 196 to 388 kN/m.

The results of the GLM found a significant main effect between clusters for event course average subjective assessments $F_{(11)}$ 9.334, $p = 0.002$, $P\eta^2 = 0.772$. Significant differences were found between clusters for subjective impact firmness ($p = 0.037$) and subjective cushioning ($p = 0.010$). Bonferroni post hoc analysis found differences between clusters 1 and 6 for both subjective assessment measurements.

Relationships between course average objective measurements included in the report and subjective surface functional properties are shown in Table 6 for the sixteen event courses included in the dataset. The strongest relationship between subjective assessments of functional properties and surface measurements was between subjective cushioning and Gmax4 (r = 0.730, $p < 0.001$). The relationship is illustrated in Figure 6. The similarity in results from subjective impact firmness and subjective cushioning was due to a very strong relationship between the scores (r = 0.885, $p < 0.001$).

	Cluster 1		Cluster 2		Cluster 3		Cluster 4		Cluster 5		Cluster 6		Cluster 7		Cluster 8		Cluster 9		Cluster 10	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Objective measurements																				
# events	6		12		15		10		13		12		7		3		2		1	
Moisture	40	57	19	65	19	37	14	36	14	36	11	39	13	35	13	26	17	18	7	7
Cushioning	7.2	8.6	8.9	10.5	10	11	10.1	12	10.9	11.6	11.5	12.3	12	12.8	12.7	12.9	13.5	13.6	13.9	13.9
Gmax4	58	71	72	82	82	91	83	95	93	101	99	107	108	112	113	117	121	123	128	128
Depth4	24	31	22	27	19	25	18	23	20	23	19	22	18	20	19	20	17	17	18	18
ER4	7	12	8	14	4	15	4	17	7	11	5	11	6	9	6	10	9	9	5	5
k2	112	162	163	208	173	224	236	279	218	280	254	320	292	331	335	351	409	443	481	481
k4	126	188	196	255	262	317	271	339	329	388	375	434	446	491	498	535	563	564	646	646
Subjective Measurements																				
# events	2		4		5		3				2									
Impact Firmness	20	33	29	55	40	62	27	64			66	79								
Cushioning	20	45	37	59	54	63	53	67			66	87								
Responsiveness	38	57	48	71	55	75	54	60			34	51								
Grip	38	89	59	83	47	72	47	91			36	56								
	BE 100		UA100		FEI4*S		FEI4*L		BE 80		BE 100		FEI4*S		UA100		UA100		UA 100	
	BE 90		FEI3*L		BEINT		FEI3*S		BE 100		UA 100		BEINT		BENOV		UA90			
	BE 90		UA100		BEINT		FEI4*L		BE 100		BE 100		UA100		BEINT					
	BEINT		FEI5*L		BEINT		FEI3*L		BEADV		FEI2*S		FEI4*S							
	BEINT		BE 100		FEI4*L		FEI4*L		FEI3*L		UA 100		FEI3*L							
	UA100		BENOV		BEINT		BENOV		BEINT		BEINT		UA100							
			FEI3*L		BENOV		BE 100		BEADV		BEADV		FEI4*S							
			UA 100		FEI3*S		FEI4*S		BENOV		UA100									
			BEINT		FEI4*L		UA 100		BE 90		BENOV									
			BEINT		UA100		BEINT		BE 100		BEADV									
			UA100		FEI4*S				FEI3*L		UA100									
			FEI5*L		BENOV				BE 100		FEI4*S									
					BE 100				BE 100											
					FEI4*L															
					BE 100															

Figure 5. The range of course average measurements used to cluster the data organized by cluster classification: moisture (%), predicted cushioning (kN), impact acceleration at 4 m/s (Gmax4) (g), penetration depth at 4 m/s (Depth4) (mm), coefficient of restitution at 4 m/s (ER4), stiffness at 2 m/s (k2) (kN/m), and stiffness at 4 m/s (k4) (kN/m). Course average subjective assessment ranges (%) are included in their allocated clusters. Impact firmness (0 = soft, 100 = hard), cushioning (0 = deep, 100 = compacted), responsiveness (0 = dead, 100 = active), grip (0 = slippery, 100 = high grip). Courses are identified and colored based on current threshold ranges used in the report. # events identify the number of events in the cluster that were used to generate minimum and maximum values for each measurement.

Table 6. Pearson correlation coefficients comparing course average objective measurements to course average subjective measures of surface functional properties (16 event course). Impact acceleration at 4 m/s (Gmax4), penetration depth at 4 m/s (Depth4), coefficient of restitution at 4 m/s (ER4), stiffness at 2 m/s (k2), and stiffness at 4 m/s (k4).

Subjective	Moisture	Predicted Cushioning	Gmax4	Depth4	ER4	k2	k4
Impact Firmness	−0.726 **	0.729 **	0.641 **	−0.564 *	0.160	0.596 *	0.644 **
Cushioning	−0.662 *	0.726 **	0.730 **	−0.572 *	−0.032	0.691 **	0.728 **
Responsiveness	−0.405	0.024	−0.139	0.247	0.097	−0.177	−0.165
Grip	−0.249	−0.061	−0.249	0.086	0.222	−0.133	−0.269

** Correlation is significant at the 0.01 level (two-tailed). * Correlation is significant at the 0.05 level (two-tailed).

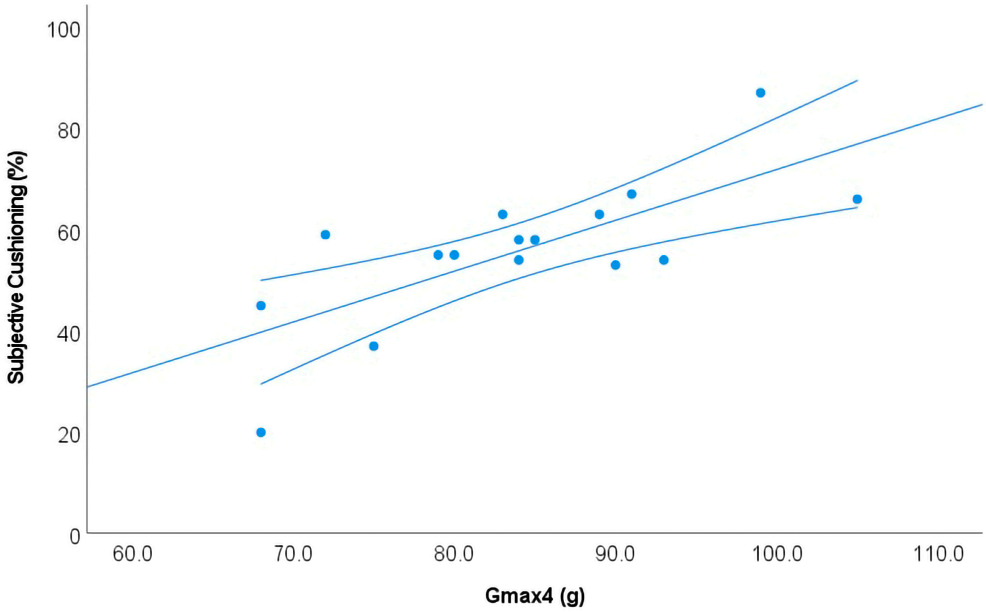

Figure 6. Scatterplot of the relationship between course averages for subjective cushioning (%) and course averages for impact acceleration at 4 m/s (GMax4) (g) from the VST. Each of the sixteen event course averages is represented by a dot. The line of best fit and 95% confidence intervals are included.

4. Discussion

This project was designed to develop and validate a practical solution for measuring eventing cross country ground. In Phase 1, course average surface functional properties were determined using a sampling strategy that tested every 250 m. Using this procedure, a key finding was that 80% of OBST cushioning could be predicted with three measurements taken from two more practical pieces of equipment for use on a cross-country course, namely, a moisture meter and a VST. Moisture had a strong relationship with OBST cushioning on turf, which confirmed the first hypothesis. Overall, the strongest relationship was between OBST cushioning and impact acceleration at 4 m/s (Gmax4) measured with the VST. As the OBST and VST are both based on measuring impact from a descending mass, this confirmed the second hypothesis. Hypothesis three was partially accepted. Event riders were able to perceive differences in impact firmness and cushioning between courses clustered by objective measurements. The strongest relationship between subjective assessments and objective measurements was with subjective cushioning and impact acceleration at 4 m/s (Gmax4).

The sampling method developed in this study was designed to provide an overall assessment of the event course on the day preceding the cross-country competition. The procedure was designed to capture the ‘galloping track’, which ranges from between 1600–2800 m at 435 m/min at the lowest level of competition (BE80) to approximately 6500 m at 570 m/min for a 5* long course. As event courses are run across varying terrain that can include parkland, fields with different soil profiles, and wooded sections [19], it is important to use a sampling distance that can provide an overall assessment of these different surfaces. In other work, determining particle size distribution from eight sample locations was found to be sufficient for characterizing North American turf grass horse racing surfaces [20]. In this study, the minimum number of sample locations for lower-level courses was nine. Clearly, turf racetracks do not have varying terrain in the same manner as event courses, however, sampling at 250 m intervals was found to capture the variation in event courses sufficiently and with reasonable effort for overall pre-competition assessment. A greater spatial resolution, including measuring prepared ground around fences, may be more appropriate during the weeks leading up to an event to assist in the preparation of the course.

Courses that were tested in Phase 1 spanned the range of conditions for eventing, from one course that was finally abandoned due to wet weather partway through the competition, to a mid-summer course with a low moisture content. Measurements from the OBST illustrated that the range of peak acceleration during impact and ground reaction forces during midstance were both above and below those produced by galloping horses [21,22]. Having a range of OBST data to compare against was essential, as both extremes have been highlighted in previous research as risk factors for injury in horses.

Excessively firm ground has been found to contribute to an increase in the magnitude of impact shock [23], peak force, and loading rates [24] in the vertical direction. In the longitudinal direction, firm ground has been shown to increase frictional forces and grip [25], shortening the duration of hoof slide and increasing the magnitude of peak longitudinal force [26]. This has been reported to increase the shearing forces that the limb experiences, which appears in the carpus prior to longitudinal limb loading [27] and can elevate the magnitude of bending moments on the cannon bone at higher speeds [28]. Conversely, firm turf surfaces with a moist grass sward can become greasy, reducing the frictional forces to the point where the surface becomes slippery. Slippery conditions can result in loss of balance, excessive joint motion, or rapid eccentric contraction of digital flexor muscles [29], potentially resulting in injury.

Excessively soft ground is known to contribute to an increase in fatigue as a result of less efficient gait [30], although the need for emergency vehicles to be able to access the course in the event of an accident or incident means that this type of ground condition is unlikely. Fatigue has been suggested to increase the risk of serious injuries up to and including death for both horse and rider [1]. Variable surfaces and longer or more demanding courses, together with other intrinsic and extrinsic factors, may contribute to an increase in fatigue. Measuring factors associated with increased injury risk is therefore an essential requirement of equipment performance.

Surface testing equipment that was included in the study was based on applicability to turf testing in other sports [31], applicability to equine surface testing [32], practical considerations for testing cross country courses, and availability. Although the equipment included was not exhaustive, the time and resources available to conduct the testing on the day before cross-country limited the number of equipment tests that could be made. As such, it was important to incorporate a range of different methods, including drop testing, penetration resistance testing, shear resistance testing, and moisture measurement.

The equipment that was used on the least number of occasions was the Going Stick. This device was originally developed for and is currently used to measure going on UK racetracks [8]. More recently, it has been used in a controlled experiment to successfully detect subsurface drainage and the addition of geotextile chips into a sand layer above which turf sods were laid [32]. In this study, a single operator took the measurements at three event courses. While further data collection was attempted, the operator was not able to fully penetrate the surface with the blade on subsequent firmer courses. As such, it was removed from the testing protocol at an early stage.

The Lang Penetrometer was selected for the study because it is small, lightweight, and easy to use, and has previously been applied to measure soil compaction. In one study, soil compaction measured with the penetrometer was identified as a factor affecting the spatial distribution of Bahiagrass and Dallisgrass on two golf courses in North Carolina [33]. In another, it was used to measure cricket outfield compaction in the Caribbean region [34]. In this study, comparisons with the OBST cushioning were promising. When using the Lang Penetrometer in Phase 2 during long periods of dry weather, courses with little or no access to water were often prepared using aerovation methods with the goal of loosening the top surface to reduce impact firmness. This method effectively spikes the ground, meaning that measuring the overall effect with a penetrometer was not possible, as the penetrometer could only measure the hole or the firm upper surface. As the chosen equipment was expected to be able to measure extremes, the penetrometer was not used in the 2022 season.

The Delta-T HH2 moisture meter and Theta Probe ML3 were selected to measure soil moisture. As with the Lang Penetrometer, these are both small and easy to operate handheld devices which can be transported around an event course. The moisture meter device has been extensively used in research to assess soil moisture in a variety of settings. and is reported to be accurate to between 0.02 and 0.04 m^3/m^3 root mean square deviation using the manufacturer's settings [35–37]. Another advantage was that the recordings can be saved with a timestamp and downloaded, which was useful for identifying locations and uploading the data into a spreadsheet. Moisture content is directly relevant to surface behavior [13,24,38]; however, the length of the rods (60 mm) limits the depth to which moisture can be measured using this device. On dry and firm event courses, inserting the probe into the ground was sometimes difficult, meaning that longer rods would not have been practical in these conditions. Other factors that should be considered alongside moisture content are soil type and root structure, both of which require further investigation.

The VST has previously been used to evaluate the softness of bedding materials for cows [17]. It was selected for this study as a drop testing device that could provide a range of metrics for comparison with OBST functional properties. It has a smaller mass than the OBST (6.15 kg versus 33 kg), a different impact shape (sphere versus hoof shape), and does not include springs or dampers in the design. As such, it does not replicate the hoof–surface interaction, which the OBST was designed to do; however, it is practical and portable enough for measuring event courses. An advantage of the method used by the VST over other simple drop test devices is that it allows for the natural variability of turf, as each location consisted of a minimum of fourteen drops on fresh ground from varying heights within a small area of each location. Measuring at different heights additionally allows for differences in the top and lower layers of turf to be reported, which organizers have found to be useful.

Subjective assessment followed the methods originally developed by Hernlund et al. [11], using a modified version of the original questionnaire to account for the differences between the show jumping and eventing disciplines. To improve the validity of the questionnaire responses [39], training was provided for the rider group who volunteered to subjectively assess the surface functional properties at events where they were competing. Key results indicated that riders' perceptions of impact firmness and cushioning were very similar, and that these were largely linked to measurements used to calculate predicted cushioning (principally GMax4 and moisture) and stiffness at 2 and 4 m/s. The similarity in results for impact firmness and cushioning may be partly due to the difference in impact shock stimuli during riding, as peak acceleration at the level of the hoof was found to be larger in drier turf compared to synthetic surfaces [21]. Additionally, visual stimuli are expected to influence haptic perception of the ground [40], whether this is due to observing a difference in moisture content or a newly harrowed surface. A previous study reported a linear relationship between subjective and objective impact firmness and a nonlinear relationship for cushioning [11]. However, when a turf venue was removed, the relationship for cushioning became linear. This suggests that the perception of cushioning may be confounded by surface type. To separate perception of impact firmness from cushioning, future guidance for the cross-country questionnaire could link impact firmness to the firmness that the rider feels when they walk the course and cushioning to the impact shock stimuli from the horse when they ride the course.

Perception of grip was impacted by whether the horse slipped while negotiating the course and depended on screw-in stud use [41], which alters the soil-shoe friction parameters [42]. Riders who completed the questionnaire on occasion commented on specific sections of the course being more slippery (unpublished verbal feedback) and rated the course overall based on these experiences.

Responsiveness was more difficult to perceive by riders, as reported previously [11].

The report format that evolved over the data collection period in 2021–2022 was initially developed from the results of the regression analysis in Phase 1 using the measurements that could predict the variability in OBST functional properties. There were exceptions; predicted cushioning was calculated from the regression equation and added to the report in order to ensure that an estimation of the forces that the horse would experience could be reported. Stiffness at 2 m/s (k2) was retained in the report to differentiate between upper and lower ground layers. Compaction measured with the Lang Penetrometer was removed from the report when these data were no longer collected. Further evaluation of functional property relationships is provided in File S2.

The final analysis was used to test how well the objective measurements mapped to ten clusters and how well riders could perceive differences between event courses. Clustering clearly differentiated courses by measurement ranges at both ends of the spectrum, and on average riders were able to perceive these differences. Most event courses spanned clusters where measurement ranges were less distinct. For these clusters, surface measurements were expected to relate to specific characteristics of the venue, and average differences between courses were not perceived by riders. This may be due to these courses falling into what may largely be described as 'good' ground, where horses might be expected to perform well. Another study found that jockeys could not perceive differences in impact firmness and cushioning between turf (no harder than good to firm) and synthetic surfaces when evaluating shoe type [43]. Confounding factors, for example those described above, along with the sensory input available to the rider may limit their ability to assess more subtle differences between surface functional properties. The thresholds established by clustering the dataset form a basis from which further data from other event courses, both nationally and internationally, can be compared in the future.

The range of courses measured over the study period was largely dependent on staff availability and access to event courses. Objective measurements covered the full range of competition levels and a good range of locations and conditions found in the UK, although fewer opportunities arose where subjective measurements could be collected. Collecting data from higher level riders was difficult at one-day events, as they had little time between disciplines and often rode several horses. In addition, despite offering training, considerable variability existed between rider assessments. Confounding factors, such as the preferred going for the horse, their cross-country performance, discussions of going prior to the competition, and changes in going between objective measurements and their cross-country round probably accounted for some of the variability. In addition, the pause in eventing due to the COVID-19 pandemic in 2020 may have impacted the results.

The effects of these limitations were that the number of event courses in each of the ten clusters was not equal, that only a small number of course-averaged subjective assessments were available, and that these did not span the full range of going. As such, the statistical power of the analyses was limited.

5. Conclusions

This project developed a practical solution for measuring eventing cross-country ground using two tools, namely, a VST and a moisture meter. These tools could predict 80% of the variability in cushioning measured with the OBST.

Subjective assessment of impact firmness and cushioning by event riders could not be discerned between the measurements, though it could be discerned between event courses when there was a clear difference in objective measurements.

An overall description of equestrian eventing cross-country ground could be determined from taking measurements at 250 m intervals.

Data were collected principally from UK event courses. However, the protocol, report, and current thresholds provide an event course baseline for future comparisons in other countries.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/biomechanics3030029/s1, File S1: Standardized protocol for measuring equestrian eventing cross-country ground. File S2: Evaluation of functional property relationships. Table S1: Rider perception of ground condition.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board (or Ethics Committee) of Nottingham Trent University (ARE202133; 20 April 2021) and University of Central Lancashire (HEALTH 0188; 28 July 2021).

Informed Consent Statement: Informed consent was obtained from the riders to collect subjective data.

Data Availability Statement: Data and an example spreadsheet are available from the corresponding author upon request at: https://uclandata.uclan.ac.uk/id/eprint/384 (accessed on 15 July 2023). The YouTube video produced for the riders https://youtu.be/gcEFCQJq_IE (accessed on 15 July 2023) can be accessed by requesting a link from alison.northrop@ntu.ac.uk.

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