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Research Paper

Operational temperatures of all-weather thoroughbred racetracks influence surface functional properties

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The surface temperature of all-weather racetracks has previously been correlated to speed. However specific functional properties such as grip, cushioning and impact firmness have not been directly compared to environmental conditions. The objective of this study was to assess how temperature influences functional properties of racetracks, and categorise surface wax binders according to first thermal transition peak, and compare responses at different operational temperatures. Functional properties were determined for UK all-weather racetrack surfaces ($n = 6$) using mechanical testing equipment which assess the loads experienced by the forelimb at gallop (randomised block design). Tests were carried out using latex lined moulds, embedded within a test box with a predefined boundary at 0 °C, 20 °C and 40 °C. Wax binders underwent differential scanning calorimetry to identify thermal transition peaks. Changes in operational temperatures significantly influenced surface responses when a wax binder was part of the composition. Temperature was a factor that significantly contributed to the variation found in horizontal grip ($F_{2,\ 237} = 65.69$, $P < 0.001$), cushioning ($F_{2,\ 237} = 58.24$, $P < 0.001$), impact firmness ($F_{2,\ 237} = 28.02$, $P < 0.001$) and rotational grip ($F_{12,\ 65} = 9.45$, $P < 0.001$). Using a test box meant individual racetracks were generalised but this enabled conditions to be controlled. Colder temperatures demonstrated higher surface hardness and shear resistance that may increase risk of musculoskeletal injury although this was not measured here. Awareness of the effect temperature has on specific track behaviour allows maintenance protocols to be further developed to improve consistency when temperatures change, with the aim of improving safety.

Abbreviations: OBST, Orono biomechanical surface tester; GWTT, Glen Withy torque tester; DSC, differential scanning calorimetry.

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1. Introduction

Evidence suggesting that UK all-weather horse racing tracks can pose a higher risk of injury than turf tracks support the need for understanding more about managing all-weather track conditions (Henley, Rogers, Harkins, & Wood, 2006; Rosanowski, Chang, Stirk, & Verheyen, 2017). All-weather surfaces usually consist of sand and fibre coated with a binder to improve drainage ability (Bardet, Jesmani, & Jabbari, 2011). Microcrystalline wax is regularly used because of its hydrophobicity, cohesive capability and high melting point, aimed at performing consistently, regardless of environmental conditions. Despite this aim, laboratory-based research has confirmed that shear strength and vertical stiffness are influenced by temperature and the binder's thermal transition regions (Bridge, Peterson, & McIlwraith, 2012; Bridge, Peterson, Radford, & McIlwraith, 2010). Temperature-related differences in the track are non-linear, meaning that surface behaviour rapidly changes as the thermal transition peaks are reached (Bridge et al., 2012). The consequences of inconsistent surface behaviour may increase risk of injury due to the hoof and associated structures experiencing varying ground reaction forces stride for stride (Kai, Takahashi, Aoki, & Oki, 1999).

Changes in surface functional properties, such as shear strength and surface stiffness, will have an impact on track performance. A correlation between the speed of horse and track temperature has been described; cooler surface temperature is correlated with faster race-times (Peterson, Reiser, Kuo, Radford, & McIlwraith, 2010). Racetracks classed as 'fast' have been considered to increase the risk of injury (Bolwell, Rogers, Gee, & McIlwraith, 2017; Zebarth & Sheard, 1985) therefore this phenomenon is a serious concern. Conversely, exceeding the transition melting temperature peak can reduce shear strength and provide less support for the horse during break-over. There is therefore a need to better understand how operational temperatures directly affect racetracks. The aim of this research was to assess the functional properties of all-weather racetrack surfaces using mechanical testing devices under controlled temperatures relevant to operational conditions. Functional properties included horizontal grip, cushioning, impact firmness and rotational grip described in detail by Hernlund et al. (2017) and Lewis et al. (2015). It was hypothesised that changes in surface temperature would significantly alter surface functional properties and that there would be differences in the range of surface responses when grouped according to the first thermal transition peak of the wax binder.

2. Materials and methods

2.1. Experimental design

Surface functional properties were quantified for samples of the UK all-weather racetrack surfaces (n = 6) under three controlled operational temperatures (0 °C, 20 °C and 40 °C) using a cross-over design (randomised block). Functional properties were measured using an Orono biomechanical surface tester (OBST) first described by Peterson, McIlwraith, and Reiser (2008) and a Glen Withy torque tester (GWTT) validated by Lewis et al. (2015). For the purpose of this study the following functional properties were measured using test devices that aim to mimic a horse's forelimb landing (OBST) or turning (GWTT) on a surface. Horizontal grip measured the distance an artificial hoof would slide forward on the surface, during loading. Cushioning was determined by measuring peak vertical force and indicated the amount of force reduction or dampening provided by the surface, including the deeper layers. Impact firmness represented hardness during hoof impact and was determined by measuring peak vertical deceleration. Rotational grip assessed surface shear resistance, giving an indication of the torque needed to turn an artificial hoof in a surface whilst applying a constant vertical load. Temperatures (0 °C, 20 °C and 40 °C) were selected, based on operating temperatures found at UK racetracks (unpublished data). Additionally, surfaces were categorised with a first thermal transition peak of either <40 °C or >40 °C.

All surfaces were prepared five times for each temperature, using the OBST (three repeated measurements in the same hoof print per preparation) and the GWTT (one measurement per preparation).

2.2. Surface preparation

A sample of each racetrack (n = 6) was oven dried for 48 h at 38 °C and rehydrated with distilled water at 4% water per dry unit mass for surfaces with a wax binder (Bridge et al., 2012) and at 12% moisture per dry unit mass for the surface with no binder (representing typical moisture content for that particular track). The rehydrated surfaces were placed in sealed containers and cooled or heated until temperatures had stabilised and stored in temperature-controlled containers until being transferred into a latex-lined mould, embedded in a test box. Time to stabilise was calculated during the pilot work. For the purposes of this investigation a stable surface temperature was defined as a consistent temperature (±2 °C) for the duration of a test date. Temperature was continuously monitored using Tinytag™ Transit 2 (Model: TG-4080) data-loggers (Gemini Data Logger Ltd., Chichester, West Sussex, UK).

The dimensions of the test box were L 1000 mm x W 980 mm x D 200 mm, selected to minimise the boundary effect on the measurements taken (Fig. 1). The test box was constructed above a compacted limestone gravel base with a geotextile membrane and synthetic silica sand providing support around a central latex-lined mould. Simulating a track surface and using this type of set-up has been described previously (Mahaffey, Peterson, & Roepstorff, 2013). The first two layers of compaction occurred at 75 mm increments and the last (top) layer was 25 mm in depth to ensure bulk density remained consistent (bulk density = 1916 kg m^{-3}).

2.3. Mechanical testing devices

The OBST was developed to mimic impact and load of the horse's forelimb with a surface using a dual-axis spring-damper mass that drops an aluminium hoof onto the surface at an angle of 8º off-set to the vertical. The OBST was

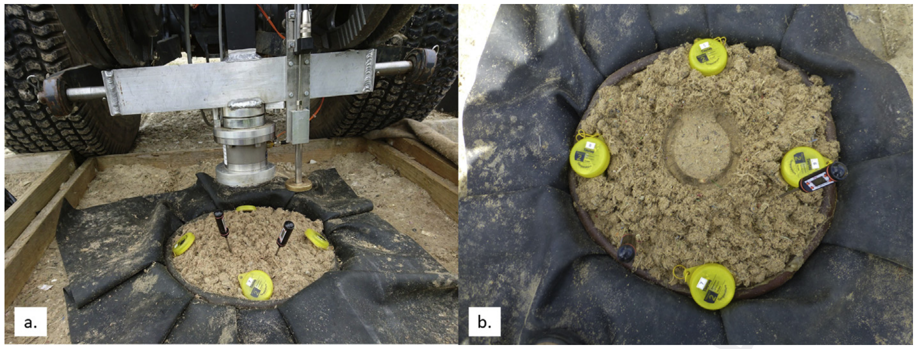

Fig. 1 – Racetrack surfaces were prepared in latex-lined moulds embedded in test boxes. (A) Temperature was continuously measured using Tinytag™ Transit 2 (Model: TG-4080) data-loggers. (B) The imprint of the hoof occurred after each surface testing device was dropped. The Orono Biomechanical Surface Tester is depicted in this specific image.

instrumented with a tri-axial accelerometer, a single axis load cell, a tri-axial load cell, a linear potentiometer and a string potentiometer (Peterson et al., 2008). The testing device was attached by three-point linkage to the back of a Kubota B-series tractor (Kubota (UK) Ltd., Thame, Oxfordshire, UK), necessary to provide appropriate stability. The GWTT reproduces rotational motion seen in horses during turning and is used to characterise shear resistance of a surface, designed as an instrumented hoof that carries 100 kg mass and measures rotational grip when dynamic grip and vertical force are applied. The instrumented hoof was lowered slowly to the ground on a three-point linkage and the equipment was turned through a measured angle of 90º. Attachment with the three-point linkage provided stability whilst the equipment was lowered vertically but it was loose enough not to interfere with rotational grip (Lewis et al., 2015).

Data was captured for 2 s in LabVIEW (LabVIEW, Berkshire, UK) at 2000 Hz for the OBST and for 10 s in LabVIEW at 100 Hz for the GWTT. Files were converted into a suitable ASCII format and imported into Visual 3D where data describing surface functional properties was extracted. Functional properties that were measured using these two mechanical testing devices were horizontal grip, cushioning, impact firmness (Hernlund et al., 2017) and rotational grip (Lewis et al., 2015).

2.4. *Heat flow rate using differential scanning calorimetry (DSC)*

The thermal properties of the wax binder present in five of the six surfaces were analysed by extracting the wax from a sample of the surface and the thermal transition of the wax binders were measured using DSC. A sample (100 g) of racetrack material underwent Soxhlet extraction to separate the wax from the sand and fibre, a method previously described elsewhere (Bardet & Sanchez, 2011). The solvent used for the extraction was high purity iso-octane and the resulting wax was analysed to calculate heat flow rates. DSC was performed in a PerkinElmer DSC6 (PerkinElmer Llantrisant, Wales, UK) under argon flow (20 ml min^{-1}). Wax samples (10 mg ± 1 mg) were heated from 15 °C to 190 °C, cooled from 190 °C–15 °C and then heated from 15 °C–190 °C in an aluminium pan as described in ASTM D4419 (2005). The DSC scans demonstrate melting enthalpies of the wax (depicted as endotherms pointing downwards) and were taken from the second heating run. The first thermal transition peak ranged between 31 °C and 45 °C meaning that thermal transitions either began before the track surface was measured at 40 °C or after 40 °C.

2.5. *Composition analysis*

Basic material analysis was conducted. The material was prepared by extracting the wax (described in section 2.4) and using a muffle oven for organic burn-off (ASTM D2974, 2007). Particle size distribution and fibre and rubber content were calculated using sieving and sedimentation techniques (ISO 11277:2009(E)). Silica sand by mass was >70.6%; polypropylene fibre and rubber was between 8.1% and 28.4%; wax by mass was between 2.3% and 6.1%. First thermal transition peak was between 31.77 °C and 43.89 °C and second thermal transition peak was between 65.29 °C and 73.75 °C.

2.6. *Data analysis*

Data were analysed using Minitab18.1 (Minitab Ltd, Coventry, UK). Differences in functional properties at 0 °C, 20 °C and 40 °C were calculated using a one-way ANOVA or Kruskal–Wallis test (according to normality), to compare tracks containing a wax binder or no wax binder. Non-linear mixed effects models were constructed with racecourse, temperature and repeat number as fixed effects. As responses in functional properties were collected from the same racecourse at a range of temperatures the temperature category was nested by racecourse. Assumptions underlying the non-linear mixed effects model were represented graphically to describe patterns of each functional property for individual racetrack. A Bonett test was used to analyse variation at each temperature by comparing magnitude of standard deviations between 0 °C, 20 °C and 40 °C.

Surfaces were categorised as containing no wax, or a wax that had its first thermal transition peak, either below 40 °C (<40 °C) or above 40 °C (>40 °C). Absolute change in each functional property (horizontal grip, cushioning, impact firmness and rotational grip) between 0 °C and 40 °C was

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calculated to indicate range of responses likely to be seen within operational temperatures, not accounting for repeated drop. Differences in range according to category were then investigated using a one-way ANOVA or Kruskal–Wallis test (according to normality). Residual values were calculated for each model and tested for normality (Kolmogorov–Smirnov) and pairwise post-hoc comparisons were performed (Tukey method).

3. Results

3.1. *Behaviour of track surfaces with and without a wax binder*

Functional properties of surfaces categorised as wax or non-wax are summarised in Table 1. Significant differences between 0 °C, 20 °C and 40 °C demonstrate how temperature influences surface material containing a wax binder whilst a surface with no wax binder appears to be less sensitive to temperature with few significant differences evident Overall, horizontal grip (slip) was 22% higher at 40 °C than at 0 °C ($F_{2, 69} = 5.79$; $P = 0.005$) and cushioning (force reduction) was 9% higher at 40 °C than at 0 °C ($F_{2,72} = 8.68$; $P < 0.001$) for all repeats of waxed surfaces. There was no significant difference in impact firmness between all three temperatures for the first impact on the waxed surfaces (4% difference between 0 °C and 40 °C) ($F_{2, 72} = 1.08$; $P = 0.347$) but the second ($H_2 = 14.70$; $P = 0.001$) and third ($H_2 = 16.49$; $P < 0.001$) impact both demonstrated 30% lower hardness at 40 °C than at 0 °C. Rotational grip demonstrated a 14% difference between the highest and lowest temperature ($F_{2,72} = 21.30$; $P < 0.001$) when considering all waxed surfaces, indicating lower shear resistance at the hotter temperatures.

3.2. *Explanatory factors for variation in functional properties*

The non-linear mixed effects models explain a significant amount of the variation in horizontal grip ($R^2 = 89.01\%$, $P < 0.001$), cushioning ($R^2 = 78.99\%$, $P < 0.001$), impact firmness ($R^2 = 87.18\%$, $P < 0.001$) and rotational grip ($R^2 = 82.32\%$, $P < 0.001$).

Temperature, as a fixed effect, was found to make a significant contribution to the variation in horizontal grip ($F_{2, 237} = 65.69$, $P < 0.001$), cushioning ($F_{2, 237} = 58.24$, $P < 0.001$), impact firmness ($F_{2, 237} = 28.02$, $P < 0.001$) and rotational grip ($F_{12, 65} = 9.45$, $P < 0.001$).

Racetrack, also a fixed effect, was found to make a significant contribution to the variation in horizontal grip ($F_{15, 237} = 11.43$, $P < 0.001$), cushioning ($F_{15, 237} = 16.94$, $P < 0.001$), impact firmness ($F_{15, 237} = 41.44$, $P < 0.001$) and rotational grip ($F_{5, 65} = 21.08$, $P < 0.001$), demonstrating that there were individual differences between racetracks.

Repeated impacts in the same location can be used to explain a significant amount of the variation for horizontal grip ($F_{2, 237} = 121.97$, $P < 0.001$), cushioning ($F_{2, 237} = 5.58$, $P = 0.004$) and impact firmness ($F_{2, 237} = 14.94$, $P < 0.001$). The first impact is indicative of a freshly prepared surface but by the second and third impact, the surface is considered to be one that has already been landed on. Rotational grip was not included in this model because the GWTT was only dropped once for each trial. Horizontal grip (i.e. the amount of slip) was significantly higher for repeat 1 than repeat 2 and 3 ($H_2 = 99.67$; $P < 0.001$) and cushioning ($H_2 = 51.07$; $P < 0.001$) and impact firmness ($H_2 = 36.01$; $P < 0.001$) were significantly lower for repeat 1 (denoting more cushioning and softer top surface) than for repeat 2 and 3, not accounting for temperature.

Table 1 – Mean (±StDev) or †median (IQR) of the surface functional properties at three temperatures (0 °C, 20 °C and 40 °C). Parametric data has been presented as mean (±StDev) and non-parametric data has been presented as median (IQR). The sample size (N) presents the five preparations for each racetrack; five tracks contained wax and one track was non-wax. Repeat drop 1, 2 and 3 are testing the same material. Letters denote heterogeneity between temperatures at a significance level of P < 0.05 (*), P < 0.01 (**) or P < 0.001 (***).

	N	Repeat Drop	Response at 0 °C	Response at 20 °C	Response at 40 °C	Significance
Horizontal grip (mm) (wax)	25	1	9.26 (1.32)b	9.07 (1.59)b	10.31 (1.13)a	**
	25	2	5.78 (1.36)b	6.32 (1.62)b	7.64 (1.08)a	***
	25	3	5.67 (1.59)b	6.12 (1.36)b	7.47 (1.26)a	***
Horizontal grip (mm) (non-wax)	5	1	8.76 (0.86)	9.72 (1.28)	10.27 (0.72)	
	5	2	5.57 (0.55)	7.12 (0.97)	6.58 (1.17)	
	5	3	5.93 (0.90)	6.63 (2.45)	7.08 (0.41)	
Cushioning (kN) (wax)	25	1	7.39 (1.15)b	8.21 (0.87)a	8.42 (0.70)a	***
	25	2	8.46 (1.20)b	9.07 (0.77)a	9.18 (0.56)a	*
	25	3	8.83 (1.15)b	9.32 (0.72)ab	9.44 (0.55)a	*
Cushioning (kN) (non-wax)	5	1	7.63 (0.32)a	7.35 (0.31)ab	7.01 (0.28)b	*
	5	2	8.44 (0.18)	8.05 (0.420)	7.76 (0.52)	
	5	3	8.89 (0.18)	8.47 (0.57)	8.36 (0.62)	
Impact firmness (g) (wax)	25	1	39.34 (9.25)	41.53 (10.60)	37.86 (6.29)	
	†25	2	57.09 (13.10)a	50.90 (16.28)	42.32 (7.5)b	***
	†25	3	58.62 (16.26)a	51.76 (16.66)a	43.56 (8.43)b	***
Impact firmness (g) (non-wax)	5	1	48.22 (1.38)	45.18 (7.47)	42.89 (5.06)	
	5	2	72.70 (9.07)	70.01 (3.58)	65.85 (6.77)	
	5	3	74.36 (4.20)	68.08 (3.04)	67.74 (4.99)	
Rotational grip (Nm) (wax)	25		33.67 (2.27)a	31.96 (2.05)b	29.23 (2.93)c	***
Rotational grip (Nm) (non-wax)	5		23.77 (1.82)	24.19 (0.98)	22.78 (1.06)	

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3.3. *Overall variation in functional properties*

There was a significantly greater variation, at 0 °C than 20 °C or 40 °C for cushioning ($P < 0.001$) and for impact firmness there was significantly greater variation at 0 °C than at 20 °C and a significantly greater variation at 20 °C than at 40 °C ($P < 0.001$). There was no significant difference between the variation found at 0 °C, 20 °C and 40 °C for horizontal grip ($P = 0.065$), or rotational grip ($P = 0.52$).

3.4. *Range of responses between 0 °C and 40 °C after categorising surfaces according to the first thermal transition peak*

Surfaces were categorised as containing no wax, or a wax that had its first thermal transition peak, either <40 °C or >40 °C and range of track responses between 0 °C and 40 °C was calculated. Differences in range of response for horizontal grip, cushioning and impact firmness was found between categories (Figs. 2–4). There was a greater range in median horizontal grip between 0 °C and 40 °C when the track material had a first thermal transition peak that was <40 °C ($F_{2,\ 71} = 11.65$; $R^2 = 23.05\%$ $P < 0.001$). Range of responses in cushioning between 0 °C and 40 °C was greater for both first thermal transition peak <40 °C and first thermal transition peak >40 °C, than for non-wax ($H_2 = 9.42$ $P = 0.009$). Range in impact firmness was significantly greater between 0 °C and 40 °C when the surface had a first thermal transition peak that was <40 °C ($F_{2,\ 81} = 8.20$; $R^2 = 25.81\%$ $P = 0.001$). There were no significant differences between the three categories for rotational grip ($F_{2,\ 27} = 1.93$; $R^2 = 12.49\%$; $P = 0.17$) (Fig. 5).

4. Discussion

All-weather track surfaces containing a wax binder demonstrated significant alterations in functional properties between 0 °C, 20 °C and 40 °C. In contrast, the track surface that contained no wax binder produced similar functional properties regardless of temperature, corroborating previous laboratory and *in-situ* findings that wax binders significantly influence surface response to temperature (Bridge et al., 2012; Peterson et al., 2010). Track managers assess and maintain surfaces according to condition (Rogers, Bolwell, Gee, Peterson, & McIlwraith, 2014), requiring them to recognise differences in functional properties that are directly relevant to the horse. Previously, however, the association between subjective and objective evaluation of equestrian surfaces has been identified as challenging (Hernlund et al., 2017). Track temperature has been seen to fluctuate more than 20 °C in one day in both the USA (Peterson et al., 2010) and in the UK (unpublished data), therefore it may be that significant information about the surface is missed, compromising surface performance and safety. The general connection between racetrack characteristics and musculoskeletal injury has been well-documented (Henley et al., 2006; Rosanowski et al., 2017) but identifying acceptable parameters to mitigate injury is not yet possible. Correlating acceptable functional properties of a surface to a specific injury is complicated by multiple factors such as horse variability and the complexity of horse-limb-landing compared with the functional properties that are measured using a testing device. The benefits of using a standardised mechanical device to compare surfaces is that functional properties from different tracks can be directly

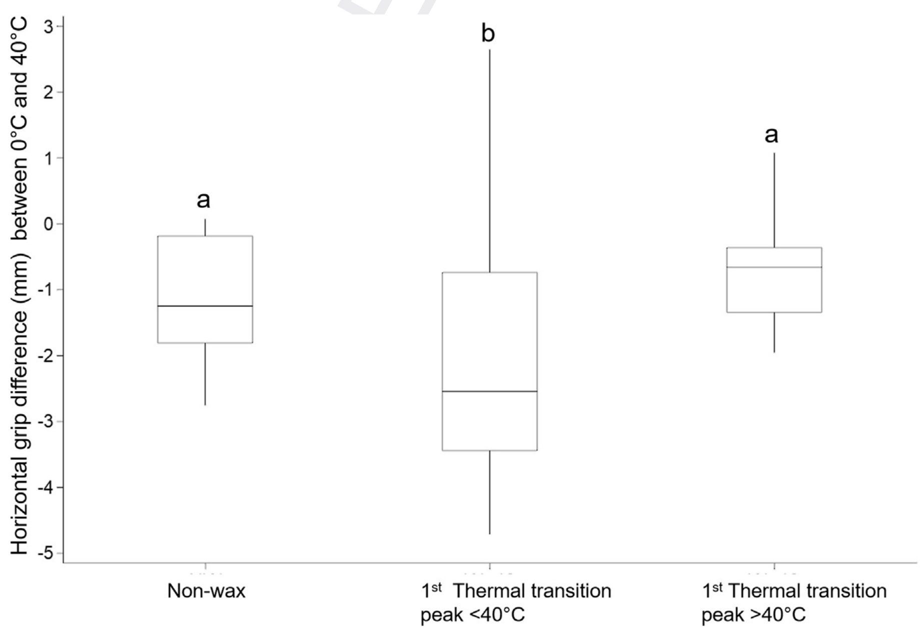

Fig. 2 — Overall difference in horizontal grip (mm) between 0 °C and 40 °C. Surfaces were categorised as Non-wax; 1st thermal transition peak <40 °C and 1st thermal transition peak>40 °C. Greater range in horizontal grip was seen in 1st thermal transition peak <40 °C ($F_{2,\ 71} = 11.65$; $R^2 = 23.05\%$ $P < 0.001$). Interquartile range and median have been demonstrated.

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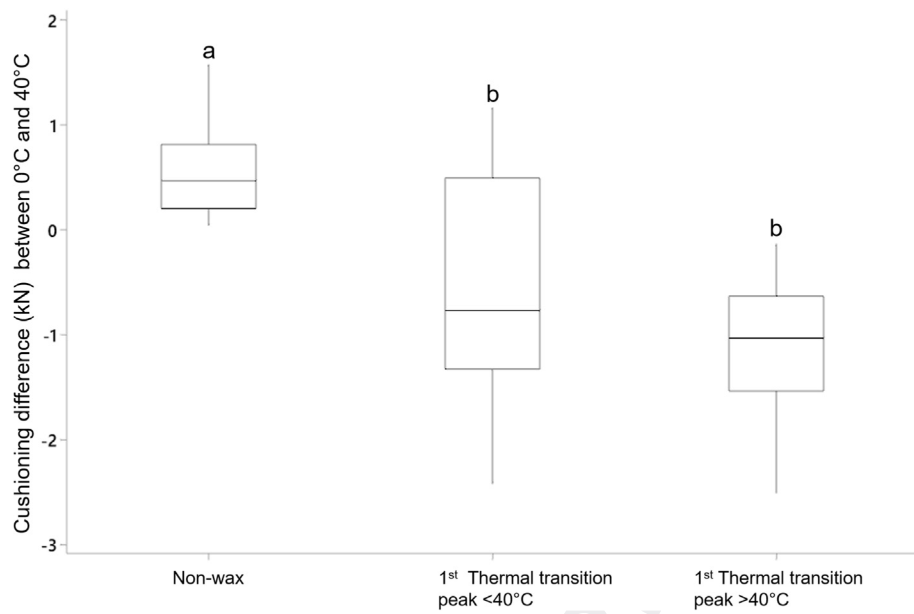

Fig. 3 – Overall difference in cushioning (kN) between 0 °C and 40 °C. Surfaces were categorised as Non-wax; 1st thermal transition peak<40 °C and 1st thermal transition peak >40 °C. Greater range in cushioning was seen in 1st thermal transition peak <40 °C and 1st thermal transition peak >40 °C than in Non-wax ($H_2 = 9.42$ $P = 0.009$). Interquartile range and median have been demonstrated.

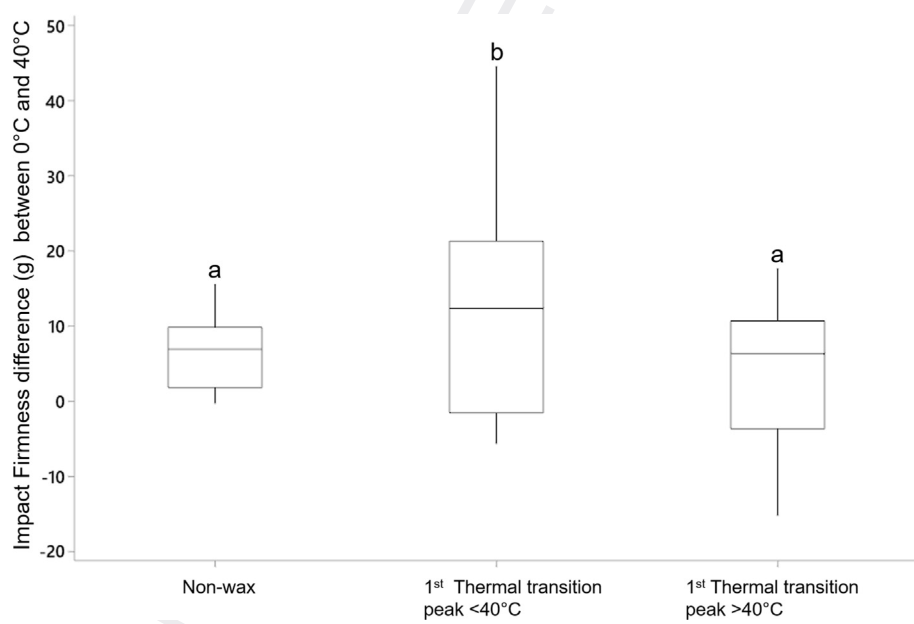

Fig. 4 – Overall difference in impact firmness (g) between 0 °C and 40 °C. Surfaces were categorised as Non-wax; 1st thermal transition peak <40 °C and 1st thermal transition peak >40 °C. Greater range in impact firmness was seen in 1st thermal transition peak <40 °C ($F_{2,\ 81} = 8.20$; $R^2 = 25.81\%$ $P = 0.001$). Interquartile range and median have been demonstrated.

compared (Hernlund et al., 2017). Whilst this current study identifies differences in surface behaviour at operational temperatures, a comparison between surface functional properties *in-situ* and against an injury database, will provide insight as to the effect the surface has on musculoskeletal horse health, which was not quantified here.

Higher surface hardness (impact firmness) and shear resistance (rotational grip), and lower slip (horizontal grip) measured at colder temperatures were likely to occur because of increased viscosity of the wax binder. Greater vertical stiffness under laboratory conditions has previously been documented when surface temperatures were lower than the first thermal transition peak, producing a more cohesive surface (Bridge et al., 2012). Stiffness of the top of the surface during primary impact would be expected to result in high impact firmness and increased grip (Hobbs et al., 2014) with

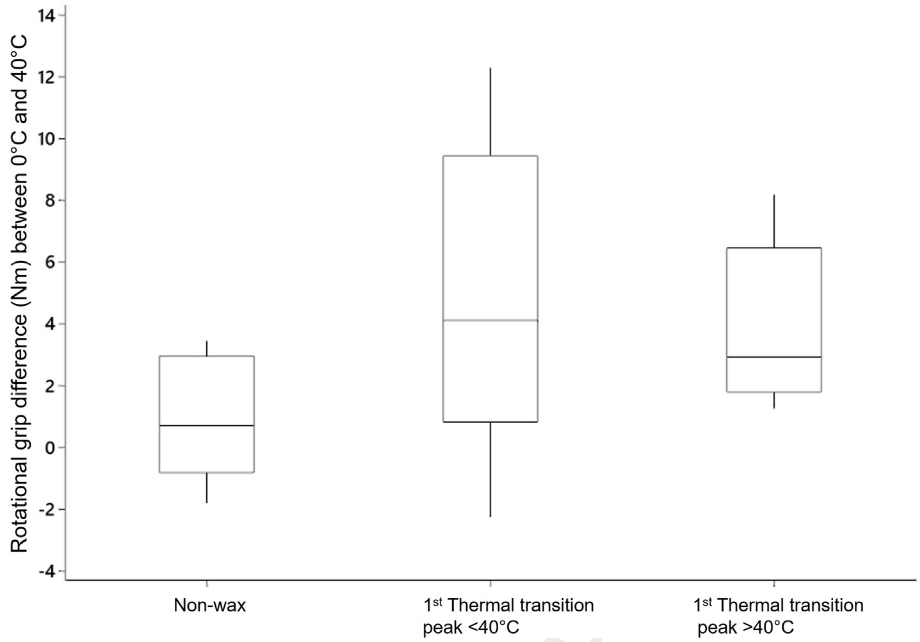

Fig. 5 – Overall difference in rotational grip (Nm) between 0 °C and 40 °C. Surfaces were categorised as Non-wax; 1st thermal transition peak <40 °C and 1st thermal transition peak >40 °C. No significant difference were evident. Interquartile range and median have been demonstrated.

wax viscosity increasing surface cohesion and subsequent compaction. At lower surface temperatures, impact firmness was 30% higher by the second and third repeat, suggesting that horses at the back of the field, or training on a track that is less frequently harrowed, will potentially experience a harder surface in colder weather. Data describing typical functional properties of all-weather racetracks have not been published to date, meaning there are no direct benchmarks for comparison. However, speed of race has been correlated with track temperature (Peterson et al., 2010) and greater damping of the surface is associated with reduced performance (speed) (Château et al., 2010).

Horizontal and rotational grip indicate shear resistance, characteristics which are important during the early phases of limb loading and the later stages of stance where propulsion occurs (Crevier-Denoix et al., 2010; Thomason & Peterson, 2008). Greater shear resistance, found at colder temperatures, would mean higher levels of friction between the surface particles and between the hoof and the surface, creating a lower amount of slip during braking and greater support for the horse during the propulsion phase of the stride (Lewis et al., 2015). At higher temperatures the wax binder may have become more ductile, resulting in a surface with lower horizontal and rotational resistance that would mean more surface deformation and less propulsive ground reaction force for the same amount of applied force by the limb. A more supportive track, seen at colder surface temperatures means less hoof displacement and a more efficient gait during the propulsion phase (Crevier-Denoix et al., 2010). Higher speeds on cold tracks may provide the horse with the opportunity to produce greater propulsion during gallop but further work is required to quantify this aspect as it was not measured here.

Conversely, optimising a track for performance (speed) may be detrimental to musculoskeletal health because greater speed, due to increased traction (Gustås, Johnston, Roepstorff & Drevemo, 2006) coupled with a harder surface (Ratzlaff, Hyde, Hutton, Rathgener & Balch, 1997) can cause a higher rate of deceleration causing the limb to experience increased impact and peak loads (Barrey, Landjerit, & Wolter, 1991). Therefore, greater impact firmness and shear resistance, seen at low surface temperatures may increase concussive forces and load that can be damaging to the horse's limbs. Epidemiological work has recognised that firmer racetracks can increase the risk of fatal injury (Henley et al., 2006) and musculoskeletal damage (Bolwell et al., 2017) whilst faster going will raise the chance of distal limb fracture (Rosanowski et al., 2017). Surface material that is not as sensitive to temperature could be developed using additives to produce tracks less prone to temperature-related variation. Additionally, greater emphasis could be placed on understanding how maintenance can mitigate these effects. Mitigation strategies such as cooling tracks by use of watering and mechanical work using a deep harrow to loosen hard surfaces are considered beneficial for consistency (Bridge, 2010). There is limited evidence from epidemiological studies identifying season as a predisposing factor for all-weather track injuries (Henley et al., 2006; Rosanowski et al., 2017); season may not be a reliable predictor of track temperature, moreover the heterogeneity of a granular surface means that individual track responses vary. The complex relationship between thermal conductivity of surface material and the stress initiated within the track at different depths as the horse lands and displaces the surface during propulsion has previously been discussed (Peterson et al., 2010). The experimental nature of this current project could not account for these factors because the surface was prepared in test boxes, however consideration should be given for these relevant issues in future work.

Findings were individual to each track, indicating that properties specific to the surface material such as fibre type, sand morphology, age and wax composition all play a role in the surface's response. The all-weather track surfaces with a wax binder contained heterogeneous fibres that demonstrated differences in characteristics such as thermal conductivity, frictional properties and hydrophobicity. Some of the fibres appeared to be stiffer in colder weather and this would contribute to the overall hardness, cushioning and shear resistance of the surface. At 0 °C a lower load (lower cushioning) was supported than at 20 °C and 40 °C. Less hydrophobic fibres were beginning to freeze at 0 °C and this may have been the reason for greater variability in cushioning at the lower temperatures. Development of fibres that are more resilient to environmental changes may help reduce such variability and create a more consistent track. There were some differences in sand particle size distribution which can influence sensitivity to moisture (Barrey et al., 1991) and may have explained some of the variation in this study. Management, environment and level of use will influence degradation, resulting in changes in surface behaviour (Bridge, Weisshaupt, Fisher, Dempsey, & Peterson, 2017). One track, due to be re-treated with wax, showed less sensitivity to temperature and tended to clump together. Wax from aged all-weather track surfaces can separate from the sand and fibre, resulting in a sticky surface due to loss of oil (Bridge, Mahaffey, & Peterson, 2014), as demonstrated here. Degradation and age appear to have a more significant impact on the oil rather than the microcrystalline wax within surface binders that over time may result in lowered thermal transition peaks (Bridge et al., 2017), a phenomenon seen in this current study.

The first thermal transition peak for the wax binder taken from the tracks was between 32 °C and 44 °C which is within normal operating track temperatures. If the first thermal transition peaks are reached, the surface would be expected to become more mobile as the wax binder begins to melt. Vertical stiffness of track material has demonstrated abrupt changes and nonlinearity prior to the first thermal transition peak in laboratory conditions (Bridge et al., 2012), a concept that could not be confirmed here because three distinctly different temperatures were measured. Tracks were categorised as containing a wax that had its first thermal transition peak either below or above 40 °C, to establish whether this affected the range of responses during operational temperatures (in this case, 0 °C–40 °C). There was a significantly greater variation of horizontal grip and impact firmness when the first thermal transition peak was <40 °C, implying that a wax with a first thermal transition peak that is within operational temperatures, may produce less consistent responses. Interestingly there were no significant differences in variation for rotational grip when surfaces were categorised according to first thermal transition peak despite finding differences in horizontal grip when using the OBST. Both these measurements are an indicator of shear resistance however the complexity of granular surfaces means that differences in test equipment influence whether the top or deeper layers of the surface shear properties are being measured. The OBST uses larger forces than the GWTT so it measures the deeper layers, and by the second and third drop the surface was more compacted (Setterbo, Fyhrie, Hubbard, Upadhyaya, & Stover, 2013). In contrast, the GWTT was only dropped once per preparation and thus had a lower sample size than the OBST; these factors were likely to contribute to the differences in findings for rotational and horizontal grip. Shear resistance is influenced by other factors, in particular the frictional properties of fibres which was not characterised here but may have significantly contributed to differences in rotational grip (Severn, Flemming and Dixon, 2010). Cushioning demonstrated higher variation in wax than non-wax surfaces, regardless of first thermal transition peak. Structural damping is influenced by the viscoelastic properties of a surface (Barrey et al., 1991) so factors such as the fibre and rubber particles will be relevant. The non-wax surface contained homogenous fibres whilst the wax surface contained a mix of heterogeneous fibre and rubber types, suggesting that factors other than thermal transition peak of the wax binder are important for cushioning and that type and quantity of fibre and rubber may have affected variation in the wax surfaces.

5. Conclusions

Colder temperatures in all-weather track surfaces demonstrate a rise in hardness and rotational grip (higher shear resistance), that may elevate speed of track although speed was not measured here. Temperature related changes such as an increase in track hardness and shear resistance may be detrimental to equine musculoskeletal health and could be considered a risk factor. Awareness of the influence temperature has on the functional properties of individual tracks means that at high-risk temperatures, racetracks could be managed more intensively to avoid fluctuations in surface behaviour. Measurements taken in this study provide information about surface functional properties but do not account for the direct consequences on performance and safety. Emphasis should now be placed on accurately measuring temperature effects *in-situ*, whilst correlating this with equine injury data and race-times.

Declaration of Competing Interest

None.

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