

1 Operational temperatures of all-weather Thoroughbred racetracks influence surface functional 2 properties

3 Abstract

4 The surface temperature of all-weather racetracks has previously been correlated to speed. However
5 specific functional properties such as grip, cushioning and impact firmness have not been directly
6 compared to environmental conditions. The objective of this study was to assess how temperature
7 influences functional properties of racetracks, and categorise surface wax binders according to first
8 thermal transition peak, and compare responses at different operational temperatures. Functional
9 properties were determined for UK all-weather racetrack surfaces ($n = 6$) using mechanical testing
10 equipment which assess the loads experienced by the forelimb at gallop (randomised block design).
11 Tests were carried out using latex lined moulds, embedded within a test box with a predefined boundary
12 at 0°C, 20°C and 40°C. Wax binders underwent differential scanning calorimetry to identify thermal
13 transition peaks. Changes in operational temperatures significantly influenced surface responses when
14 a wax binder was part of the composition. Temperature was a factor that significantly contributed to the
15 variation found in horizontal grip ($F_{2, 237} = 65.69, P < 0.001$), cushioning ($F_{2, 237} = 58.24, P < 0.001$), impact
16 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
17 individual racetracks were generalised but this enabled conditions to be controlled. Colder temperatures
18 demonstrated higher surface hardness and shear resistance that may increase risk of musculoskeletal
19 injury although this was not measured here. Awareness of the effect temperature has on specific track
20 behaviour allows maintenance protocols to be further developed to improve consistency when
21 temperatures change, with the aim of improving safety.

22 **Keywords:** operational temperatures, shear resistance, impact firmness, horse hoof-surface-
23 interaction, functional properties

24 Nomenclature

25 OBST Orono biomechanical surface tester

26 GWTT Glen Withy torque tester

27 DSC differential scanning calorimetry

28 1. Introduction

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

42

43 Changes in surface functional properties, such as shear strength and surface stiffness, will have an
44 impact on track performance. A correlation between the speed of horse and track temperature has been
45 described; cooler surface temperature is correlated with faster race-times (Peterson, Reiser, Kuo,
46 Radford & McIlwraith, 2010). Racetracks classed as 'fast' have been considered to increase the risk of
47 injury (Zebarth & Sheard, 1985; Bolwell, Rogers, Gee & McIlwraith, 2017) therefore this phenomenon
48 is a serious concern. Conversely, exceeding the transition melting temperature peak can reduce shear
49 strength and provide less support for the horse during break-over. There is therefore a need to better
50 understand how operational temperatures directly affect racetracks. The aim of this research was to
51 assess the functional properties of all-weather racetrack surfaces using mechanical testing devices
52 under controlled temperatures relevant to operational conditions. Functional properties included
53 horizontal grip, cushioning, impact firmness and rotational grip described in detail by Hernlund et al.
54 (2017) and Lewis et al. (2015). It was hypothesised that changes in surface temperature would
55 significantly alter surface functional properties and that there would be differences in the range of
56 surface responses when grouped according to the first thermal transition peak of the wax binder.

57

58 **2. Materials and Methods**

59 **2.1. Experimental design**

60 Surface functional properties were quantified for samples of the UK all-weather racetrack surfaces (n =
61 6) under three controlled operational temperatures (0°C, 20°C and 40°C) using a cross-over design
62 (randomised block). Functional properties were measured using an Orono biomechanical surface tester
63 (OBST) first described by Peterson, McIlwraith and Reiser (2008) and a Glen Withy torque tester
64 (GWTT) validated by Lewis et al. (2015). For the purpose of this study the following functional properties
65 were measured using test devices that aim to mimic a horse's forelimb landing (OBST) or turning
66 (GWTT) on a surface. Horizontal grip measured the distance an artificial hoof would slide forward on
67 the surface, during loading. Cushioning was determined by measuring peak vertical force and indicated
68 the amount of force reduction or dampening provided by the surface, including the deeper layers. Impact
69 firmness represented hardness during hoof impact and was determined by measuring peak vertical
70 deceleration. Rotational grip assessed surface shear resistance, giving an indication of the torque
71 needed to turn an artificial hoof in a surface whilst applying a constant vertical load. Temperatures (0°C,
72 20°C and 40°C) were selected, based on operating temperatures found at UK racetracks (unpublished
73 data). Additionally, surfaces were categorised with a first thermal transition peak of either <40°C or >
74 40°C.

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

78 **2.2 Surface preparation**

79 A sample of each racetrack (n = 6) was oven dried for 48 h at 38°C and rehydrated with distilled water
80 at 4% water per dry unit mass for surfaces with a wax binder (Bridge et al., 2012) and at 12% moisture
81 per dry unit mass for the surface with no binder (representing typical moisture content for that particular
82 track). The rehydrated surfaces were placed in sealed containers and cooled or heated until
83 temperatures had stabilised and stored in temperature-controlled containers until being transferred into
84 a latex-lined mould, embedded in a test box. Time to stabilise was calculated during the pilot work. For
85 the purposes of this investigation a stable surface temperature was defined as a consistent temperature

86 ($\pm 2^{\circ}\text{C}$) for the duration of a test date. Temperature was continuously monitored using TinytagTM Transit
87 2 (Model: TG-4080) data-loggers (Gemini Data Logger Ltd., Chichester, West Sussex, UK).

88 The dimensions of the test box were L 1000 mm x W 980 mm x D 200 mm, selected to minimise the
89 boundary effect on the measurements taken (Fig 1). The test box was constructed above a compacted
90 limestone gravel base with a geotextile membrane and synthetic silica sand providing support around
91 a central latex-lined mould. Simulating a track surface and using this type of set-up has been described
92 previously (Mahaffey, Peterson & Roepstorff, 2013). The first two layers of compaction occurred at 75
93 mm increments and the last (top) layer was 25 mm in depth to ensure bulk density remained consistent
94 (bulk density= $1,916\text{ kg m}^{-3}$).

95 **2.3. Mechanical testing devices**

96 The OBST was developed to mimic impact and load of the horse's forelimb with a surface using a dual-
97 axis spring-damper mass that drops an aluminium hoof onto the surface at an angle of 8° off-set to the
98 vertical. The OBST was instrumented with a tri-axial accelerometer, a single axis load cell, a tri-axial
99 load cell, a linear potentiometer and a string potentiometer (Peterson et al., 2008). The testing device
100 was attached by three-point linkage to the back of a Kubota B-series tractor (Kubota (UK) Ltd., Thame,
101 Oxfordshire, UK), necessary to provide appropriate stability. The GWTT reproduces rotational motion
102 seen in horses during turning and is used to characterise shear resistance of a surface, designed as an
103 instrumented hoof that carries 100 kg mass and measures rotational grip when dynamic grip and vertical
104 force are applied. The instrumented hoof was lowered slowly to the ground on a three-point linkage and
105 the equipment was turned through a measured angle of 90° . Attachment with the three-point linkage
106 provided stability whilst the equipment was lowered vertically but it was loose enough not to interfere
107 with rotational grip (Lewis et al., 2015).

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

113 **2.4. Heat flow rate using differential scanning calorimetry (DSC)**

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

126 **2.5. Composition analysis**

127 Basic material analysis was conducted. The material was prepared by extracting the wax (described in
128 section 2.4) and using a muffle oven for organic burn-off (ASTM D2974). Particle size distribution and
129 fibre and rubber content were calculated using sieving and sedimentation techniques (ISO
130 11277:2009(E)). Silica sand by mass was >70.6 %; polypropylene fibre and rubber was between 8.1 %
131 and 28.4 %; wax by mass was between 2.3 % and 6.1 %. First thermal transition peak was between
132 31.77 °C and 43.89 °C and second thermal transition peak was between 65.29°C and 73.75°C.

133

134 **2.6. Data analysis**

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

142 individual racetrack. A Bonett test was used to analyse variation at each temperature by comparing
143 magnitude of standard deviations between 0°C, 20°C and 40°C.

144 Surfaces were categorised as containing no wax, or a wax that had its first thermal transition peak,
145 either below 40°C (<40°C) or above 40°C (>40°C). Absolute change in each functional property
146 (horizontal grip, cushioning, impact firmness and rotational grip) between 0°C and 40°C was calculated
147 to indicate range of responses likely to be seen within operational temperatures, not accounting for
148 repeated drop. Differences in range according to category were then investigated using a one-way
149 ANOVA or Kruskal-Wallis test (according to normality). Residual values were calculated for each model
150 and tested for normality (Kolmogorov-Smirnov) and pairwise post-hoc comparisons were performed
151 (Tukey method).

152

153 **3. Results**

154 **3.1. Behaviour of track surfaces with and without a wax binder**

155 Functional properties of surfaces categorised as wax or non-wax are summarised in Table 1. Significant
156 differences between 0°C, 20°C and 40°C demonstrate how temperature influences surface material
157 containing a wax binder whilst a surface with no wax binder appears to be less sensitive to temperature
158 with few significant differences evident Overall, horizontal grip (slip) was 22% higher at 40°C than at
159 0°C ($F_{2,69} = 5.79$; $P = 0.005$) and cushioning (force reduction) was 9% higher at 40°C than at 0°C ($F_{2,72}$
160 $= 8.68$; $P < 0.001$) for all repeats of waxed surfaces. There was no significant difference in impact
161 firmness between all three temperatures for the first impact on the waxed surfaces (4% difference
162 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 ($H_2 =$
163 16.49 ; $P < 0.001$) impact both demonstrated 30% lower hardness at 40°C than at 0°C . Rotational grip
164 demonstrated a 14% difference between the highest and lowest temperature ($F_{2,72} = 21.30$; $P < 0.001$)
165 when considering all waxed surfaces, indicating lower shear resistance at the hotter temperatures.

166

167 **3.2. Explanatory factors for variation in functional properties**

168 The non-linear mixed effects models explain a significant amount of the variation in horizontal grip (R^2
169 = 89.01%, $P < 0.001$), cushioning ($R^2 = 78.99\%$, $P < 0.001$), impact firmness ($R^2 = 87.18\%$, $P < 0.001$) and
170 rotational grip ($R^2 = 82.32\%$, $P < 0.001$).

171 Temperature, as a fixed effect, was found to make a significant contribution to the variation in horizontal
172 grip ($F_{2, 237} = 65.69$, $P < 0.001$), cushioning ($F_{2, 237} = 58.24$, $P < 0.001$), impact firmness ($F_{2, 237} =$
173 28.02 , $P < 0.001$) and rotational grip ($F_{12, 65} = 9.45$, $P < 0.001$).

174 Racetrack, also a fixed effect, was found to make a significant contribution to the variation in horizontal
175 grip ($F_{15, 237} = 11.43$, $P < 0.001$), cushioning ($F_{15, 237} = 16.94$, $P < 0.001$), impact firmness ($F_{15, 237} =$
176 41.44 , $P < 0.001$) and rotational grip ($F_{5, 65} = 21.08$, $P < 0.001$), demonstrating that there were individual
177 differences between racetracks.

178 Repeated impacts in the same location can be used to explain a significant amount of the variation for
179 horizontal grip ($F_{2, 237} = 121.97$, $P < 0.001$), cushioning ($F_{2, 237} = 5.58$, $P = 0.004$) and impact firmness ($F_{2,$
180 $237} = 14.94$, $P < 0.001$). The first impact is indicative of a freshly prepared surface but by the second and
181 third impact, the surface is considered to be one that has already been landed on. Rotational grip was
182 not included in this model because the GWTT was only dropped once for each trial. Horizontal grip (i.e.
183 the amount of slip) was significantly higher for repeat 1 than repeat 2 and 3 ($H_2 = 99.67$; $P < 0.001$) and
184 cushioning ($H_2 = 51.07$; $P < 0.001$) and impact firmness ($H_2 = 36.01$; $P < 0.001$) were significantly lower
185 for repeat 1 (denoting more cushioning and softer top surface) than for repeat 2 and 3, not accounting
186 for temperature.

187

188 **3.3. Overall variation in functional properties**

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

193

194 **3.4. Range of responses between 0°C and 40°C after categorising surfaces according to the first**
195 **thermal transition peak**

196 Surfaces were categorised as containing no wax, or a wax that had its first thermal transition peak,
197 either <40°C or >40°C and range of track responses between 0°C and 40°C was calculated.
198 Differences in range of response for horizontal grip, cushioning and impact firmness was found between
199 categories (Figs. 2-4). There was a greater range in median horizontal grip between 0°C and 40°C
200 when the track material had a first thermal transition peak that was <40°C ($F_{2, 71} = 11.65$; $R^2 = 23.05\%$
201 $P < 0.001$). Range of responses in cushioning between 0°C and 40°C was greater for both first thermal
202 transition peak <40°C and first thermal transition peak >40°C, than for non-wax ($H_2 = 9.42$ $P = 0.009$).
203 Range in impact firmness was significantly greater between 0°C and 40°C when the surface had a first
204 thermal transition peak that was <40°C ($F_{2, 81} = 8.20$; $R^2 = 25.81\%$ $P = 0.001$). There were no significant
205 differences between the three categories for rotational grip ($F_{2, 27} = 1.93$; $R^2 = 12.49\%$; $P = 0.17$) (Fig.
206 5).

207

208

209 **4. Discussion**

210 All-weather track surfaces containing a wax binder demonstrated significant alterations in functional
211 properties between 0°C, 20°C and 40°C. In contrast, the track surface that contained no wax binder
212 produced similar functional properties regardless of temperature, corroborating previous laboratory and
213 *in-situ* findings that wax binders significantly influence surface response to temperature (Bridge et al.,
214 2012; Peterson et al., 2010). Track managers assess and maintain surfaces according to condition
215 (Rogers, Bolwell, Gee, Peterson & McIlwraith, 2014), requiring them to recognise differences in
216 functional properties that are directly relevant to the horse. Previously, however, the association
217 between subjective and objective evaluation of equestrian surfaces has been identified as challenging
218 (Hernlund et al., 2017). Track temperature has been seen to fluctuate more than 20°C in one day in
219 both the USA (Peterson et al., 2010) and in the UK (unpublished data), therefore it may be that
220 significant information about the surface is missed, compromising surface performance and safety. The
221 general connection between racetrack characteristics and musculoskeletal injury has been well-

222 documented (Henley et al., 2006; Rosanowski et al., 2017) but identifying acceptable parameters to
223 mitigate injury is not yet possible. Correlating acceptable functional properties of a surface to a specific
224 injury is complicated by multiple factors such as horse variability and the complexity of horse-limb-
225 landing compared with the functional properties that are measured using a testing device. The benefits
226 of using a standardised mechanical device to compare surfaces is that functional properties from
227 different tracks can be directly compared (Hernlund et al., 2017). Whilst this current study identifies
228 differences in surface behaviour at operational temperatures, a comparison between surface functional
229 properties *in-situ* and against an injury database, will provide insight as to the effect the surface has on
230 musculoskeletal horse health, which was not quantified here.

231 Higher surface hardness (impact firmness) and shear resistance (rotational grip), and lower slip
232 (horizontal grip) measured at colder temperatures were likely to occur because of increased viscosity
233 of the wax binder. Greater vertical stiffness under laboratory conditions has previously been
234 documented when surface temperatures were lower than the first thermal transition peak, producing a
235 more cohesive surface (Bridge et al., 2012). Stiffness of the top of the surface during primary impact
236 would be expected to result in high impact firmness and increased grip (Hobbs et al., 2014) with wax
237 viscosity increasing surface cohesion and subsequent compaction. At lower surface temperatures,
238 impact firmness was 30% higher by the second and third repeat, suggesting that horses at the back of
239 the field, or training on a track that is less frequently harrowed, will potentially experience a harder
240 surface in colder weather. Data describing typical functional properties of all-weather racetracks have
241 not been published to date, meaning there are no direct benchmarks for comparison. However, speed
242 of race has been correlated with track temperature (Peterson et al., 2010) and greater damping of the
243 surface is associated with reduced performance (speed) (Château et al., 2010).

244

245 Horizontal and rotational grip indicate shear resistance, characteristics which are important during the
246 early phases of limb loading and the later stages of stance where propulsion occurs (Thomason &
247 Peterson, 2008; Crevier-Denoix et al., 2010). Greater shear resistance, found at colder temperatures,
248 would mean higher levels of friction between the surface particles and between the hoof and the
249 surface, creating a lower amount of slip during braking and greater support for the horse during the
250 propulsion phase of the stride (Lewis et al., 2015). At higher temperatures the wax binder may have

251 become more ductile, resulting in a surface with lower horizontal and rotational resistance that would
252 mean more surface deformation and less propulsive ground reaction force for the same amount of
253 applied force by the limb. A more supportive track, seen at colder surface temperatures means less
254 hoof displacement and a more efficient gait during the propulsion phase (Crevier-Denoix et al., 2010).
255 Higher speeds on cold tracks may provide the horse with the opportunity to produce greater propulsion
256 during gallop but further work is required to quantify this aspect as it was not measured here.

257

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

279

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

299

300 The first thermal transition peak for the wax binder taken from the tracks was between 32°C and 44°C
301 which is within normal operating track temperatures. If the first thermal transition peaks are reached,
302 the surface would be expected to become more mobile as the wax binder begins to melt. Vertical
303 stiffness of track material has demonstrated abrupt changes and nonlinearity prior to the first thermal
304 transition peak in laboratory conditions (Bridge et al., 2012), a concept that could not be confirmed here
305 because three distinctly different temperatures were measured. Tracks were categorised as containing
306 a wax that had its first thermal transition peak either below or above 40°C, to establish whether this
307 affected the range of responses during operational temperatures (in this case, 0°C to 40°C). There was
308 a significantly greater variation of horizontal grip and impact firmness when the first thermal transition

309 peak was <40°C, implying that a wax with a first thermal transition peak that is within operational
310 temperatures, may produce less consistent responses. Interestingly there were no significant
311 differences in variation for rotational grip when surfaces were categorised according to first thermal
312 transition peak despite finding differences in horizontal grip when using the OBST. Both these
313 measurements are an indicator of shear resistance however the complexity of granular surfaces means
314 that differences in test equipment influence whether the top or deeper layers of the surface shear
315 properties are being measured. The OBST uses larger forces than the GWTT so it measures the deeper
316 layers, and by the second and third drop the surface was more compacted (Setterbo, Fyhrie, Hubbard,
317 Upadhyaya & Stover, 2013). In contrast, the GWTT was only dropped once per preparation and thus
318 had a lower sample size than the OBST; these factors were likely to contribute to the differences in
319 findings for rotational and horizontal grip. Shear resistance is influenced by other factors, in particular
320 the frictional properties of fibres which was not characterised here but may have significantly contributed
321 to differences in rotational grip (Severn, Flemming and Dixon, 2010). Cushioning demonstrated higher
322 variation in wax than non-wax surfaces, regardless of first thermal transition peak. Structural damping
323 is influenced by the viscoelastic properties of a surface (Barrey et al., 1991) so factors such as the fibre
324 and rubber particles will be relevant. The non-wax surface contained homogenous fibres whilst the wax
325 surface contained a mix of heterogeneous fibre and rubber types, suggesting that factors other than
326 thermal transition peak of the wax binder are important for cushioning and that type and quantity of fibre
327 and rubber may have affected variation in the wax surfaces.

328

329 **5. Conclusions**

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

338 accurately measuring temperature effects *in-situ*, whilst correlating this with equine injury data and race-
 339 times.

340

341 **TABLE 1** Mean (\pm StDev) or [†]median (IQR) of the surface functional properties at three temperatures
 342 (0°C, 20°C and 40°C). Parametric data has been presented as mean (\pm StDev) and non-parametric
 343 data has been presented as median (IQR). The sample size (N) presents the five preparations for each
 344 racetrack; five tracks contained wax and one track was non-wax. Repeat drop 1, 2 and 3 are testing the
 345 same material. Letters denote heterogeneity between temperatures at a significance level of $P < 0.05$ (*),
 346 $P < 0.01$ (**) or $P < 0.001$ (***).

347

348

349

	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	25	1	39.34 (9.25)	41.53 (10.60)	37.86 (6.29)	
firmness (g)	†25	2	57.09 (13.10)a	50.90 (16.28)	42.32 (7.5)b	***
(wax)	†25	3	58.62 (16.26)a	51.76 (16.66)a	43.56 (8.43)b	***
Impact	5	1	48.22 (1.38)	45.18 (7.47)	42.89 (5.06)	
firmness (g)	5	2	72.70 (9.07)	70.01 (3.58)	65.85 (6.77)	
(non-wax)	5	3	74.36 (4.20)	68.08 (3.04)	67.74 (4.99)	
Rotational grip	25		33.67 (2.27)a	31.96 (2.05)b	29.23 (2.93)c	***
(Nm) (wax)						
Rotational grip	5		23.77 (1.82)	24.19 (0.98)	22.78(1.06)	
(Nm) (non-wax)						

350

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

355

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

360

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

365

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

370

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

374

375 **Declarations of interest:**

376 None

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