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1 **Manuscript title**

2 **The challenges of equestrian arena surfaces: the unprecedented use of a raised platform at the**
3 **2012 Olympic Games**

4

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6

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26 **Abstract**

27 The design of equestrian arenas can be challenged by time constraints and specific restrictions at a
28 venue but are nonetheless a critical element to the success and sustainability of equestrian sport. The
29 equestrian arenas for the 2012 Olympic Games were an example of a temporary arena constructed
30 on a raised platform and supported by struts, a design unprecedented for equestrian activities. This
31 study assessed the developmental stages of the Olympic surfaces from 2011 to the actual event in
32 2012 and aimed to confirm that accelerations and forces experienced by horses were comparable to
33 those on solid ground. Assessment took place at i) the Olympic test-event; ii) a developmental mock-
34 up arena and iii) the Olympic venue in 2012. A Clegg impact hammer measured peak vertical
35 deceleration and an Orono Biomechanical Surface Tester quantified peak load and peak loading rate.
36 General Linear Models using the arena's structural features as explanatory variables highlighted
37 surface heterogeneity. Peak vertical deceleration ($P < .0001$) and peak load ($P < .0001$) were
38 significantly higher and peak loading rate was significantly lower ($P < .0001$) following iterative testing
39 and modifications to the arena. Data were comparable with surfaces on solid ground by the final
40 testing at the 2012 Olympic Games. Findings highlighted the importance of testing surfaces
41 throughout their development and demonstrated the impact that surface composition, time elapsed
42 since installation, water management, and type of construction have on surface functional properties,
43 with relevance to future temporary arena initiatives.

44

45 **Keywords:** Equestrian arena surfaces; horse; peak load and loading rate; Olympic Games;
46 equestrian sport

47

48

49 **1. Introduction**

50 The primary aim of a purpose-built equestrian arena is to maintain horse and rider safety whilst
51 supporting optimal performance, a challenge because characteristics for these criteria can be
52 conflicting. Equine footing with greater damping capabilities for example, attenuates concussive
53 stress and could protect against associated orthopaedic injury [1] however, this may result in loss of
54 power during propulsion that can be detrimental to performance [2]. Ensuring that arena constructions
55 are fit for purpose means assessing surface functional properties that are relevant to the horse and

56 the type of activities being performed [3]. Temporary competition arenas have the added challenge of
57 consolidation in a short time but there is limited evidence to recommend processes used to produce
58 and assess this type of arena. In-situ mechanical testing devices intended to mimic the interaction
59 between the horse and the surface have the advantage of directly comparing one surface to another,
60 yet such equipment tends to simplify the complexity of the limb's structure and are unable to replicate
61 stance duration in its entirety [4]. Mechanical testing equipment can assess impact firmness and
62 cushioning. Impact firmness is measured by vertical deceleration that describes surface stiffness
63 during initial impact on limb landing [5]. Peak load is calculated to give a measure of cushioning and
64 determines force reduction during mid-stance when the limb is loaded maximally [6]. Additionally,
65 loading rate provides information about the rate of force development experienced by the limb and
66 depends on compliance of the surface during impact [5]. Surface functional properties such as impact
67 firmness and cushioning, are accounted for by the surface composition [1], the base layer [7] and
68 other factors pertinent to construction such as irrigation, maintenance, and time available for the
69 surface to establish.

70

71 The equestrian arenas for the 2012 Olympic Games were developed on a temporary raised platform,
72 suspended by a series of support struts, unprecedented for equestrian activities. This paper reports
73 the process and outcomes of a project that aimed to assess the surface functional properties
74 throughout the development of the arenas produced for the 2012 Olympic Games. It was
75 hypothesised that dynamic loading of the surface would be altered by modifications in surface
76 composition, moisture content and construction. The details of this project demonstrate the approach
77 taken to optimise an arena surface at a high-profile event and are of relevance to future arena
78 assessment and construction.

79

80

81 **2. Materials and Methods**

82 **2.1 Study protocol**

83 The equestrian arenas for the 2012 Olympic Games were designed using a unique raised platform to
84 accommodate the varied topography and protect the rare acid grassland at Greenwich Park, London,
85 UK, a UNESCO World Heritage Site. The Olympic Committee organised a test-event for the

86 equestrian disciplines one year in advance, as preparation. One aim of the test event was to identify
87 aspects of surface construction and preparation that could be refined prior to the Olympic Games in
88 2012. Surface performance was assessed using mechanical test equipment. Peak vertical
89 deceleration was measured using a Clegg impact hammer and an Orono Biomechanical Surface
90 Tester (OBST) was used to quantify peak load and peak loading rate (Figure 1A-B). Riders gave
91 informal feedback to the Olympic Committee to help support decisions in design, but these were not
92 recorded as part of this project.

93

94 Following mechanical assessments and an equivocal, anecdotal rider-response from invited riders at
95 the test-event, two small arenas were constructed at an outdoor test site in the UK. An arena was built
96 on a raised platform (30 m by 15 m) with support struts, replicating the temporary arena at Greenwich
97 Park and a developmental track was built on solid ground (30 m by 5 m), used as a control.
98 Mechanical testing of these arenas took place between November 2011 and March 2012. The
99 developmental arena on a raised platform underwent several iterations of surface composition,
100 determined by the surface provider, and not described in detail here. General composition of these
101 surfaces were washed, silicic sand, polypropylene fibres, and a polymer binder used as a
102 hydrophobic coating to the sand. Classification of sand particle size was predominantly within the
103 medium to very fine range (0.05-0.5 mm). Data from the 2011 test-event surface (TS1), an
104 intermediate surface early on at the developmental arena (TS2) and the final test surface later-on at
105 the developmental arena (TS3) have been reported here. Final assessments were conducted at
106 Greenwich Park, London using TS3, two weeks prior to the equestrian events starting in 2012.

107

108 **2.2. Experimental set-up**

109 A systematic sampling technique allowed data to be collected across the whole arena using as high a
110 resolution as possible in the time available (Table 1). Arenas were marked out with a grid to ensure
111 that data was collected from the whole surface. Differences in time required for each test device, time
112 available for sampling at each site due to security constraints, and differences in arena dimensions
113 resulted in variable sample sizes. A two-phase approach to testing was undertaken, as described
114 below.

115

116 **2.2.1. Phase One: comparison between data collected on the raised platform at Greenwich**
117 **Park 2011 test-event before and after competition and a comparable arena constructed on**
118 **solid ground.**

119 Assessment immediately prior to the test-event at Greenwich Park in 2011 identified the surface
120 (TS1), was not conducive to optimal performance, this finding was supported by anecdotal evidence
121 given to the Olympic Committee by invited riders. Therefore, immediately after the event, the surface
122 was re-tested following additional maintenance (irrigation and use rollers and harrows), however the
123 sample size was smaller because a course of fences were set up for another competition. The data
124 collected before and after the 2011 test-event was compared against an established arena that had a
125 similar surface composition to TS1 and acted as a control. The control was constructed on solid
126 ground and had been laid >12 months prior to testing. Primary differences between the two arena
127 surfaces were time for surface consolidation (namely, temporary *versus* a permanent competition
128 arena) and base layer construction (Figure 2A-C). Base layer construction at Greenwich Park
129 included a specialised water management system of interlocking modular geocellular units
130 (Permavoid 150, Permavoid™ Amsterdam, The Netherlands). The control arena was constructed on
131 solid ground with a limestone base layer and was regularly used for affiliated dressage and show-
132 jumping competitions. Additionally, surface functional properties were measured on-strut and off-strut
133 and were compared for the elevated arena (Greenwich Park).

134

135 **2.2.3. Phase Two: developmental arenas and the 2012 Olympic Games arena immediately prior**
136 **to the event**

137 It was evident that surface consolidation occurred differently on the two arenas tested in Phase One.
138 Phase Two aimed to assess and develop surface performance on a raised arena that would support a
139 load comparable to that found on a surface built on solid ground, whilst removing any differences
140 between measurements on-struts and off-struts. The construction of the raised platform during this
141 phase included some alterations since the 2011 test-event; 150 mm of MOT type 1 Specification for
142 Highway Works Series 800 [8] was added on top of the platform base. The MOT type 1 was
143 strengthened with Tensar 2000 geogrid (Tensar International Ltd, Blackburn, UK), laid at 75 mm
144 within the MOT type 1 and used as a polymeric stiffener prior to the Permavoid™ units (Figure 2C). All
145 surfaces were developed by the surface-provider, with the aim of improving rate of consolidation and

146 supporting optimal performance. Phase Two was used to assess the functional properties of an
147 intermediate surface (TS2) and the final surface (TS3) on a modified raised platform and these were
148 compared to a track on solid ground (control) laid with the initial surface (TS1). Additionally, surface
149 functional properties were measured on-strut and off-strut, and these were compared against each
150 other and solid ground. The final tests were conducted at Greenwich Park, immediately prior to the
151 2012 Olympic Games using TS3 and a modified arena construction.

152

153 **2.3. Mechanical and physical surface assessment**

154 Peak vertical deceleration was measured using a Clegg impact hammer. A weight of 2.25 kg was
155 dropped from a height of 0.45 m four times on the same location using a standard procedure [9]. The
156 highest reading achieved from the four drops was recorded as peak vertical deceleration, described
157 as being the most repeatable measure [10]. Peak load and peak loading rate were captured from
158 three drops on the same location of the Orono Biomechanical Surface Tester (OBST) for 2 s in
159 LabVIEW™ (LabVIEW, Berkshire, UK) at 2000 Hz. Data presented here is for the first drop on each
160 location. The OBST was first described for use on racetracks [11] and more recently for arena
161 surfaces [4]. The OBST was constructed on two rails, with the long rail at an angle of 8° from the
162 vertical, dropping a spring damper mass (33 kg) onto the surface from 0.86 m, allowing it to simulate
163 vertical and horizontal loading of a horse's forelimb landing on a surface [12]. Files were converted
164 into a suitable ASCII format and imported into Visual 3D to extract peak load and peak loading rate.
165 Moisture content was influenced by precipitation and sub-surface irrigation. Laboratory analyses of
166 100 g samples were conducted to determine moisture content by oven drying at 40°C for 48 hours
167 and calculating percentage of moisture loss using a modified version of ISO/TS 17892-1:2004.

168

169 **2.4 Temperature data**

170 Hourly temperature data (°C) was obtained retrospectively for each test date and taken from the UK
171 national meteorological service (Met Office metoffice.gov.uk), as an indicator of ambient temperature
172 during days of testing.

173

174 **2.4. Statistical Analysis**

175 Data were analysed using Minitab 19™ (Minitab Ltd, Coventry, UK) with the significance set at $P < 0.05$
176 and assessed for normality using Kolmogorov-Smirnov test. Descriptive data of peak vertical
177 deceleration, peak load and peak loading rate were established. Greenwich Park 2011 test-event was
178 assessed before and after the competition and compared to a similar competition arena surface, not
179 on a platform and analysed using a one-way ANOVA or Kruskal-Wallis test according to normality.

180

181 General Linear Models using the arena's structural features (raised platform; raised platform
182 reinforced with MOT Type 1; on solid ground), date, and surface type (TS1; TS2; TS3) as explanatory
183 variables, were used to highlight surface heterogeneity (peak vertical deceleration, peak load, and
184 peak loading rate). The Greenwich Park 2011 test-event, the developmental arena, and the final
185 surface at Greenwich Park prior to the 2012 Olympic Games were compared. Moisture was included
186 as a covariate.

187

188 A two-sample *t*-test or Mann-Whitney U test were used to compare differences between on-strut and
189 off-strut for peak vertical deceleration, peak load, and peak loading rate at the Greenwich test-event
190 (TS1). Differences between on-strut, off-strut and solid ground for peak vertical deceleration, peak
191 load and peak loading rate were compared during the developmental work, using a one-way ANOVA
192 or Kruskal-Wallis test.

193

194

195 **3. Results**

196

197 **3.1. Comparison between data on the platform at Greenwich Park 2011 test-event before and** 198 **after competition and a comparable arena on solid ground (Phase One)**

199 Data from Greenwich Park 2011 test-event before competition demonstrated a significantly lower
200 peak vertical deceleration ($H_{2,107}=54.18$; $P < .0001$), peak load ($F_{2,69}=146.52$; $P < .0001$) and loading
201 rate ($H_{2,107}=94.88$; $P < .0001$) than after the Greenwich Park 2011 test-event, both of which were
202 significantly lower than the control which was a comparable, established competition arena, not
203 constructed on a platform (Table 2).

204

205 **3.2. Developmental platform compared to solid ground and the 2012 Olympic Games arena**
206 **(Phase Two)**

207 Data collected from the developmental arenas in Phase Two identified that surface type ($F_{2,119} = 3.63$;
208 $P = .029$), date ($F_{4,119} = 30.15$; $P < .0001$) and construction ($F_{2,119} = 35.10$; $P < .0001$) significantly
209 affected peak vertical deceleration; ($R^2 = 73.49\%$). Surface type ($F_{2,117} = 6.61$; $P = .002$), date ($F_{4,117} =$
210 8.47 ; $P < .0001$) and construction ($F_{2,117} = 23.41$; $P < .0001$) also had a significant effect on peak load
211 ($R^2 = 54.35\%$). Similarly, surface type ($F_{2,117} = 12.43$; $P < .0001$), date ($F_{4,117} = 6.94$; $P < .0001$) and
212 construction ($F_{2,117} = 16.88$; $P < .0001$) significantly affected peak loading rate ($R^2 = 55.78\%$). Figure 3-
213 5 illustrate the differences in the functional properties assessed during the developmental work.

214

215 Significant differences in surface type and construction in peak vertical deceleration, peak load and
216 peak loading rate are summarised in Table 3. Peak vertical deceleration was significantly higher for
217 TS3 on the platform than for TS1 or TS2 ($F_{5,94} = 17.38$; $P < .0001$). Peak vertical deceleration was
218 comparable between the final surface for the 2012 Olympic Games and on solid ground during the
219 developmental work. Peak load was significantly higher on the developmental platform when the final
220 surface type (TS3) was used ($F_{5,93} = 22.37$; $P < .0001$) and these higher peak loads were evident at
221 the 2012 Olympic Games arena, whilst being comparable with measurements taken on solid ground.
222 Peak loading rate was significantly lower at the 2012 Olympic Games ($F_{5,92} = 68.46$; $P < .0001$),
223 compared to the developmental platform and solid ground.

224

225 **3.3 Differences between on-strut and off-strut for i) the 2011 test-event and ii) the**
226 **developmental platform**

227 There were no significant differences in peak vertical deceleration or peak loading rate between on-
228 strut and off-strut during the whole project (Figs. 3,5). Significant differences in peak load between on-
229 strut and off-strut during the 2011 test-event ($T_{1,54} = 3.51$; $P = .001$) were no longer evident by March
230 2012 in Phase Two when comparing peak load between on-strut, off-strut and on solid ground ($F_{2,16} =$
231 3.11 ; $P = .057$) (Fig. 4).

232

233

234 **4. Discussion**

235 Competing horses on a raised platform was unique, therefore careful examination was necessary to
236 ensure that surface functional properties were analogous to those that horses would have typically
237 trained and previously competed on. Comparing vertical deceleration, peak load, and peak loading
238 rate between a raised surface and one on solid ground and between on and off struts, were integral to
239 decisions leading to the construction of the arenas for the Olympic Games in 2012. Surface
240 composition, time since installation, water management and arena construction significantly
241 influenced the surface's mechanical behaviour. These findings were essential to the successful
242 construction of a temporary arena on a raised platform and subsequently produced surface functional
243 properties comparable to those measured on solid ground. The significance of this study goes beyond
244 describing the development of a unique arena; it provides evidence of how all elements of the arena
245 construction influences surface functional properties which are directly relevant to horse and rider
246 performance and ultimately, safety.

247

248 Similarities between surfaces used for training and competition have been noted as important in
249 humans [13,14] and horses [7], thus allowing specificity of training so the athlete is appropriately
250 prepared for performance. The temporary 2011 test-event surface produced significantly lower peak
251 vertical deceleration, peak load, and peak loading rate than a permanent training and competition
252 arena with a similar composition but a different base structure, used as a benchmark. Moreover, the
253 objective assessment of the surface was confirmed by riders who anecdotally described the surface
254 as heavy and unresponsive. At the time of testing (2011-2012) there was no standard reference
255 dictating ideal range, partly because of limited evidence connecting standardised objective surface
256 measurements to orthopaedic injuries in horses [3]. However, a low peak load can mean the surface
257 is less able to support the horse during mid-stance and propulsion because the whole surface yields
258 more readily [15]. The result is a higher stride frequency and greater propulsive effort to maintain the
259 same speed [2] that can increase muscular effort [16] and negatively influence performance [2].

260 Therefore, to produce an appropriate competition surface, there was a need to develop a stiffer
261 surface profile that supported a higher peak load. Increased peak loads can be generated through
262 greater compaction of surface particles [17], which was achieved during the developmental work in
263 this project. Conversely, vertical deceleration and loading rate indicate surface hardness, that if too
264 high, can cause concussive stress during impact [18] and has been implicated in musculoskeletal

265 injury in racehorses [19,20]. Reducing impact shock associated with loading rate but still providing an
266 acceptable level of support (peak load) will be beneficial for performance whilst minimising the
267 damaging effect of concussion during primary and secondary impact [6]. The final surface for the
268 2012 Olympic Games (TS3) arising as an outcome of our repeated and iterative testing, produced
269 higher peak loads and therefore greater support whilst maintaining moderate vertical deceleration and
270 loading rates. This was considered favourable for performance and musculoskeletal health,
271 corroborated by anecdotal rider response to the surface.

272

273 Surface composition is directly related to surface behaviour [21] and is therefore an important facet to
274 surface construction. Although specific composition details are protected for commercial reasons, its
275 combination of sand, fibre, and a polymer binder proved valuable. Sand angularity, for instance,
276 affects how easily particles interlock and therefore consolidate. Similarly, the frictional properties of
277 fibre will influence stability and shear resistance [22] whilst fibre hydrophobicity and pore space
278 between particles are related to water holding capacity. At the 2011 test-event, moisture content was
279 low during surface settling, limiting rate of consolidation, thus producing a surface that was mobile
280 and less able to support a horse during peak performance. Moisture content influences cohesion of
281 sand particles and frictional damping [1], both of which are relevant, particularly as a surface becomes
282 established. Additives such as a polymer binder, used here, will reduce the need for water by
283 increasing surface cohesion when compared to non-coated sand, whilst improving drainage due to
284 hydrophobic properties [23]. Irrespective of additives, data from the 2011 test-event demonstrated the
285 need for water during surface consolidation. Temporary surfaces benefit from materials and
286 maintenance that allow rapid consolidation of the surface. However, shear resistance must not
287 increase to such an extent that it prevents the hoof from sliding in the surface. Longitudinal and
288 rotational grip were unable to be measured for this study but would be considered necessary for a
289 more complete understanding of how the surface responds. Hoof motion through the surface will
290 depend upon the surface properties and the manoeuvres that the horse is performing [24]. Shear
291 resistance is directly relevant to movements such as turning and pushing off and is therefore
292 important for horses competing at events such as the Olympic Games. At the time of this study, there
293 were few testing devices that could reliably differentiate the shear resistance between surfaces but
294 should be an important consideration for future work.

295

296 Polymer binders such as the one used here, will become more cohesive and even brittle at lower
297 temperatures, whilst in warmer conditions greater surface displacement is likely as the binder
298 becomes less viscous [25]. Under laboratory conditions, synthetic surfaces produce greater vertical
299 stiffness when the polymer binder has not yet reached its first thermal transition peak [26], thereby
300 creating a harder surface. Peak loading rate and vertical deceleration was highest for TS3 at the
301 developmental arena which can, in part, be explained by ambient temperatures not reaching typical
302 thermal transition peaks. However, measurements of TS3 taken prior to the 2012 Olympic Games
303 were at a point when ambient temperatures were high enough for the binder to begin to melt. Typical
304 first thermal transition temperatures in surface binders are between 30 °C and 45 °C meaning that
305 changes in mechanical properties would be expected as these temperatures are neared [27]. There is
306 a need to further investigate surface functional properties at operational temperatures to understand
307 this more fully. The findings from this current work demonstrate the importance of analysing surface
308 composition to gain a thorough understanding of overall performance under specific conditions.

309

310 The base layer is a further important consideration in surface assessment. Substances within the
311 base layer may alter surface damping such as woodchip [28] or a recycling water system
312 (Permavoid™ units) [17] that provide a degree of area elasticity rather than point elasticity that is
313 ordinarily seen in arena surfaces [6]. Area elasticity means a larger area of the surface is deflected on
314 application of a downward force, a phenomenon that is likely to occur if there is more flexibility to the
315 lower levels of the surface such as when the arena is constructed on a raised platform, as illustrated
316 here. Other examples that could create this effect would be a well-designed fibre sand top layer or turf
317 with a deep root system, both with optimal moisture. Struts under the base layer supported the
318 platform and measurements at the test event in 2011 demonstrated significant differences in peak
319 load between measurements on and off a strut, identifying lack of uniformity. It is hypothesised that
320 the small movements allowed between the struts lessened compaction of the top layer contributing to
321 the differences in peak load. An uneven surface will initiate unpredictable forces through the limb thus
322 increasing risk of injury [29,30] and reducing horse confidence [6] and therefore performance. Horses
323 demonstrate small but significant differences in limb posture when the surface is subtly altered [31]
324 and can adjust limb retraction when moving from distinctly different surfaces [32]. The ability to modify

325 gait as an immediate short-term response is advantageous to avoid stumbling or falling however, a
326 non-uniform surface would repeatedly increase muscle activation necessary to maintain posture that
327 could increase muscle fatigue and risk of injury [32]. The third iteration of the surface (TS3) at the
328 developmental arena demonstrated no significant differences in peak load on and off strut by the last
329 test date. Machinery used to expedite surface consolidation on solid ground include vibration rollers
330 which, at the 2011 test-event were incapable of compacting the surface on a raised platform,
331 particularly aspects of the surface that were not directly supported by a strut. Vibration rollers were
332 not therefore used during arena preparation in 2012 for the Olympic Games. Improved uniformity
333 between on and off strut was considered to be due to increased base layer stiffness and surface
334 consolidation arising from structural modifications of the platform. Differences between on-strut and
335 off-strut peak vertical deceleration and peak loading rate were not detected throughout testing. The
336 Clegg Impact hammer is a lightweight device that assesses hardness (peak vertical deceleration) of
337 granular material whilst peak loading rate explains rate of force production during hoof impact. As
338 such, the Clegg hammer only characterises the top layers of the surface, and loading rate is
339 influenced by the top layer. It is therefore unsurprising that differences in the base layer were not
340 distinguished by these specific measurements. Decisions on sampling resolution were made based
341 on position of struts, size of the arenas and time available. It is possible that information about overall
342 surface uniformity was missed because the sampling resolution was too low [4]. Future work to
343 identify a sampling resolution that is representative of the entire arena would be a valuable tool in
344 calculating surface uniformity. Nonetheless, our findings demonstrate the importance of evaluating
345 overall performance under specific conditions and highlight the need for a responsive and
346 collaborative approach to arena construction by an interdisciplinary team that includes suppliers,
347 event organisers and scientists.

348

349 **5. Conclusion**

350 The novel design for the equestrian arenas at the 2012 Olympic Games highlighted the importance of
351 developing standard test equipment and protocols that can reliably assess the functional properties of
352 equine surfaces. The arenas constructed on a temporary raised platform were successfully modified
353 to produce vertical deceleration, peak load, and peak loading rate, comparable to those found on
354 competition surfaces built on the ground. The findings from this work illustrate the need to pay

355 particular attention to arena base construction regardless of its architecture, because of its role in
356 supporting the horse during maximal effort. Additionally, design related challenges such as those
357 encountered at this venue guided the development of surface composition, demonstrating the value of
358 surface specificity to ensure it is fit for purpose.

359

360 **Declaration of interest**

361 None.

362

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367

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446 **Figure Captions**

447 Fig 1 (A) The Orono Biomechanical Surface Tester. (B) Assessment of the equestrian arenas at
448 Greenwich Park test event 2011.

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450 Fig 2 Schematic of equestrian arena construction and surface layers for A) Greenwich Park 2011 test
451 event, established on a raised platform; B) a comparable arena constructed on solid ground and C)
452 Greenwich Park 2012 Summer Olympics, established on a raised platform.

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454 Fig 3 Mean (\pm SD) peak vertical deceleration (g) on the developmental test arena identifying
455 differences between surface type and construction, within date (22 December 2011 $P < .0001$ $F_{2,36} =$
456 15.56; 7 January 2012 $P = .027$ $H_{2,30} = 7.21$; 23 January 2012 $*P = .005$ $H_{4,24} = 14.87$). On solid
457 ground was made up of the initial surface material, TS2 was the intermediate surface material and
458 TS3 was the final surface material. $*P < .05$; $**P < .01$; $***P < .001$.

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460 Fig 4 Mean (\pm SD) peak load (kN) on the developmental test arena identifying differences between
461 surface type and construction, within date (7 January 2012 $P < .0001$ $F_{2,30} = 14.61$; 23 January 2012;
462 $P < .0001$ $F_{4,24} = 14.82$; 15 February 2012 $P = .013$ $T_{1,11} = 3.18$). On solid ground was made up of the
463 initial surface material, TS2 was the intermediate surface material and TS3 was the final surface
464 material. $*P < .05$; $**P < .01$; $***P < .001$.

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468 Fig 5 Mean (\pm SD) peak loading rate (kN/s) on the developmental test arena identifying differences
469 between surface type and construction, within date (7 January 2012 $P < .0001$ $F_{2,30} = 10.92$; 23
470 January 2012 $P < .0001$ $F_{4,24} = 15.06$). On solid ground was made up of the initial surface material,
471 TS2 was the intermediate surface material and TS3 was the final surface material. $***P < .001$.

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TABLE 1 Details of sampling resolution and arena dimensions for all phases of the project

Arena	Sample size	Dimensions: length (m)	Dimensions: width (m)
Phase 1: 2011 Greenwich test-event	34	80	70
Phase 1: Comparable arena	39	80	30
Phase 2: Developmental arena (raised platform)	12-37	30	15
Phase 2: Developmental track (ground)	7	30	5
Phase 3: Pre-2012 Olympics	24	100	80

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TABLE 2 Results for Phase 1. Mean \pm SD for peak vertical deceleration (g), peak load (kN) and peak loading rate (kN/s) for the 2011 test-event before and after the competition and an established comparable competition arena on solid ground. Letters (^{a-c}) denote significant differences at the level of $P < 0.0001$.

	Greenwich Park 2011 (Pre-test- event)	(CV) / Variance	Greenwich Park 2011 (Post-test- event)	(CV) / Variance	Comparable arena	(CV) / Variance
Construction	Platform		Platform		Solid ground	
n	32		37		39	
Peak vertical deceleration (g)	78.63 \pm 7.77 ^c	9.88/60.31	88.54 \pm 7.36 ^b	8.31 / 54.44	104.59 \pm 17.66 ^a	16.88/311.7 2
Peak load (kN)	8.30 \pm 0.68	8.15 / 0.46	9.02 \pm 0.69	7.70 / 0.48	11.71 \pm 1.18	10.09/1.40
Peak loading rate (kN/s)	852.6 \pm 80.00 ^c	9.37 / 6405.1	1919.4 \pm 203.2 ^b	10.58 / 41271.7	4820 \pm 804 ^a	16.69 / 646903

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512 **TABLE 3** Mean \pm SD for peak vertical deceleration (g), peak load (kN) and peak loading rate (kN/s)
513 and temperature ($^{\circ}$ C) for all surface iterations. Letters (^{a-d}) denote significant differences ($P < 0.0001$)
514 between surface type and construction for peak vertical deceleration, peak load, and peak loading
515 rate.

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Surface type and construction	Peak vertical deceleration (g)	Peak load (kN)	Peak loading rate (kN/s)	Daily (approximate) ambient temperature $^{\circ}$ C
2011 Greenwich test-event (TS1)	78.63 \pm 7.77 ^c	8.30 \pm 0.68 ^b	852.6 \pm 80.0 ^d	28.56 \pm 1.01
Early developmental (TS2 platform)	75.41 \pm 2.52 ^c	8.49 \pm 0.42 ^b	1264.4 \pm 104.7 ^b	7.72 \pm 0.89
Early developmental (TS1 ground)	83.70 \pm 1.15 ^{bc}	9.62 \pm 0.21 ^a	1562.4 \pm 42.3 ^a	7.72 \pm 0.89
Final developmental (TS3 platform)	99.33 \pm 7.50 ^a	9.48 \pm 0.47 ^a	1551.8 \pm 118.7 ^a	9.06 \pm 2.01
Final developmental (TS1 ground)	95.70 \pm 2.68 ^{ab}	9.59 \pm 0.24 ^a	1591.5 \pm 52.9 ^a	9.06 \pm 2.01
2012 Olympic surface (TS3)	88.08 \pm 13.71 ^b	9.60 \pm 0.64 ^a	1032.7 \pm 123.8 ^c	26.22 \pm 1.79

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