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

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Abstract

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

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

1. Introduction

The primary aim of a purpose-built equestrian arena is to maintain horse and rider safety whilst supporting optimal performance, a challenge because characteristics for these criteria can be conflicting. Equine footing with greater damping capabilities for example, attenuates concussive stress and could protect against associated orthopaedic injury [1] however, this may result in loss of power during propulsion that can be detrimental to performance [2]. Ensuring that arena constructions are fit for purpose means assessing surface functional properties that are relevant to the horse and the type of activities being performed [3]. Temporary competition arenas have the added challenge of consolidation in a short time but there is limited evidence to recommend processes used to produce and assess this type of arena. In-situ mechanical testing devices intended to mimic the interaction between the horse and the surface have the advantage of directly comparing one surface to another, yet such equipment tends to simplify the complexity of the limb's structure and are unable to replicate stance duration in its entirety [4]. Mechanical testing equipment can assess impact firmness and cushioning. Impact firmness is measured by vertical deceleration that describes surface stiffness during initial impact on limb landing [5]. Peak load is calculated to give a measure of cushioning and determines force reduction during mid-stance when the limb is loaded maximally [6]. Additionally, loading rate provides information about the rate of force development experienced by the limb and depends on compliance of the surface during impact [5]. Surface functional properties such as impact firmness and cushioning, are accounted for by the surface composition [1], the base layer [7] and other factors pertinent to construction such as irrigation, maintenance, and time available for the surface to establish.

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

2. Materials and Methods

2.1 Study protocol

The equestrian arenas for the 2012 Olympic Games were designed using a unique raised platform to accommodate the varied topography and protect the rare acid grassland at Greenwich Park, London, UK, a UNESCO World Heritage Site. The Olympic Committee organised a test-event for the equestrian disciplines one year in advance, as preparation. One aim of the test event was to identify aspects of surface construction and preparation that could be refined prior to the Olympic Games in 2012. Surface performance was assessed using mechanical test equipment. Peak vertical deceleration was measured using a Clegg impact hammer and an Orono Biomechanical Surface Tester (OBST) was used to quantify peak load and peak loading rate (Figure 1A-B). Riders gave informal feedback to the Olympic Committee to help support decisions in design, but these were not recorded as part of this project.

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

2.2. Experimental set-up

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

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

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

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

It was evident that surface consolidation occurred differently on the two arenas tested in Phase One. Phase Two aimed to assess and develop surface performance on a raised arena that would support a load comparable to that found on a surface built on solid ground, whilst removing any differences between measurements on-struts and off-struts. The construction of the raised platform during this phase included some alterations since the 2011 test-event; 150 mm of MOT type 1 Specification for Highway Works Series 800 [8] was added on top of the platform base. The MOT type 1 was strengthened with Tensar 2000 geogrid (Tensar International Ltd, Blackburn, UK), laid at 75 mm within the MOT type 1 and used as a polymeric stiffener prior to the Permavoid^{TM} units (Figure 2C). All surfaces were developed by the surface-provider, with the aim of improving rate of consolidation and supporting optimal performance. Phase Two was used to assess the functional properties of an intermediate surface (TS2) and the final surface (TS3) on a modified raised platform and these were compared to a track on solid ground (control) laid with the initial surface (TS1). Additionally, surface functional properties were measured on-strut and off-strut, and these were compared against each other and solid ground. The final tests were conducted at Greenwich Park, immediately prior to the 2012 Olympic Games using TS3 and a modified arena construction.

2.3. Mechanical and physical surface assessment

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

2.4 Temperature data

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

2.4. Statistical Analysis

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

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

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

3. Results

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

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

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

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

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

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

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

4. Discussion

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

Similarities between surfaces used for training and competition have been noted as important in humans [13,14] and horses [7], thus allowing specificity of training so the athlete is appropriately prepared for performance. The temporary 2011 test-event surface produced significantly lower peak vertical deceleration, peak load, and peak loading rate than a permanent training and competition arena with a similar composition but a different base structure, used as a benchmark. Moreover, the objective assessment of the surface was confirmed by riders who anecdotally described the surface as heavy and unresponsive. At the time of testing (2011-2012) there was no standard reference dictating ideal range, partly because of limited evidence connecting standardised objective surface measurements to orthopaedic injuries in horses [3]. However, a low peak load can mean the surface is less able to support the horse during mid-stance and propulsion because the whole surface yields more readily [15]. The result is a higher stride frequency and greater propulsive effort to maintain the same speed [2] that can increase muscular effort [16] and negatively influence performance [2]. Therefore, to produce an appropriate competition surface, there was a need to develop a stiffer surface profile that supported a higher peak load. Increased peak loads can be generated through greater compaction of surface particles [17], which was achieved during the developmental work in this project. Conversely, vertical deceleration and loading rate indicate surface hardness, that if too high, can cause concussive stress during impact [18] and has been implicated in musculoskeletal injury in racehorses [19,20]. Reducing impact shock associated with loading rate but still providing an acceptable level of support (peak load) will be beneficial for performance whilst minimising the damaging effect of concussion during primary and secondary impact [6]. The final surface for the 2012 Olympic Games (TS3) arising as an outcome of our repeated and iterative testing, produced higher peak loads and therefore greater support whilst maintaining moderate vertical deceleration and loading rates. This was considered favourable for performance and musculoskeletal health, corroborated by anecdotal rider response to the surface.

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

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

The base layer is a further important consideration in surface assessment. Substances within the base layer may alter surface damping such as woodchip [28] or a recycling water system (Permavoid^{TM} units) [17] that provide a degree of area elasticity rather than point elasticity that is ordinarily seen in arena surfaces [6]. Area elasticity means a larger area of the surface is deflected on application of a downward force, a phenomenon that is likely to occur if there is more flexibility to the lower levels of the surface such as when the arena is constructed on a raised platform, as illustrated here. Other examples that could create this effect would be a well-designed fibre sand top layer or turf with a deep root system, both with optimal moisture. Struts under the base layer supported the platform and measurements at the test event in 2011 demonstrated significant differences in peak load between measurements on and off a strut, identifying lack of uniformity. It is hypothesised that the small movements allowed between the struts lessened compaction of the top layer contributing to the differences in peak load. An uneven surface will initiate unpredictable forces through the limb thus increasing risk of injury [29,30] and reducing horse confidence [6] and therefore performance. Horses demonstrate small but significant differences in limb posture when the surface is subtly altered [31] and can adjust limb retraction when moving from distinctly different surfaces [32]. The ability to modify gait as an immediate short-term response is advantageous to avoid stumbling or falling however, a non-uniform surface would repeatedly increase muscle activation necessary to maintain posture that could increase muscle fatigue and risk of injury [32]. The third iteration of the surface (TS3) at the developmental arena demonstrated no significant differences in peak load on and off strut by the last test date. Machinery used to expedite surface consolidation on solid ground include vibration rollers which, at the 2011 test-event were incapable of compacting the surface on a raised platform, particularly aspects of the surface that were not directly supported by a strut. Vibration rollers were not therefore used during arena preparation in 2012 for the Olympic Games. Improved uniformity between on and off strut was considered to be due to increased base layer stiffness and surface consolidation arising from structural modifications of the platform. Differences between on-strut and off-strut peak vertical deceleration and peak loading rate were not detected throughout testing. The Clegg Impact hammer is a lightweight device that assesses hardness (peak vertical deceleration) of granular material whilst peak loading rate explains rate of force production during hoof impact. As such, the Clegg hammer only characterises the top layers of the surface, and loading rate is influenced by the top layer. It is therefore unsurprising that differences in the base layer were not distinguished by these specific measurements. Decisions on sampling resolution were made based on position of struts, size of the arenas and time available. It is possible that information about overall surface uniformity was missed because the sampling resolution was too low [4]. Future work to identify a sampling resolution that is representative of the entire arena would be a valuable tool in calculating surface uniformity. Nonetheless, our findings demonstrate the importance of evaluating overall performance under specific conditions and highlight the need for a responsive and collaborative approach to arena construction by an interdisciplinary team that includes suppliers, event organisers and scientists.

5. Conclusion

The novel design for the equestrian arenas at the 2012 Olympic Games highlighted the importance of developing standard test equipment and protocols that can reliably assess the functional properties of equine surfaces. The arenas constructed on a temporary raised platform were successfully modified to produce vertical deceleration, peak load, and peak loading rate, comparable to those found on competition surfaces built on the ground. The findings from this work illustrate the need to pay particular attention to arena base construction regardless of its architecture, because of its role in supporting the horse during maximal effort. Additionally, design related challenges such as those encountered at this venue guided the development of surface composition, demonstrating the value of surface specificity to ensure it is fit for purpose.

Declaration of interest

None.

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Figure Captions

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

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

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

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

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

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

TABLE 2 Results for Phase 1. Mean ± 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 ± 7.77^{c}	9.88/60.31	88.54 ± 7.36^{b}	8.31 / 54.44	104.59 ± 17.66 ^{a}	16.88/311.72
Peak load (kN)	8.30 ± 0.68	8.15 / 0.46	9.02 ± 0.69	7.70 / 0.48	11.71 ± 1.18	10.09/1.40
Peak loading rate (kN/s)	852.6 ± 80.00^{c}	9.37 / 6405.1	1919.4 ± 203.2^{b}	10.58 / 41271.7	4820 ± 804^{a}	16.69 / 646903

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

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