

Comparison of equipment used to measure shear properties in equine arena surfaces

Lewis, Kate, Northrop, Alison J, Crook, Glen Martin, Mather, John, Martin, Jaime H, Holt, Danielle, Clayton, Hilary M, Roepstorff, Lars, Peterson, Michael and Hobbs, Sarah Jane

1 **Abstract**

2 The design of a novel apparatus, the Glen Withy torque tester (GWTT), for measuring
3 horizontal shear properties in equine sport surfaces is described. Previous research has
4 considered the effect of vertical loading on equine performance and injury but only limited
5 discussion has concerned the grip or horizontal motion of the hoof. The horizontal support of
6 the hoof by the surface must be sufficient to avoid excess slip without overloading the limb.
7 The GWTT measures the torque necessary to twist an artificial hoof that is being pushed into
8 the surface under a consistently applied vertical load. Its output was validated using a steel
9 surface, then was used to test two sand and fibre surfaces (waxed and non-waxed) through
10 rotations of 40-140°, and vertical loads of 156-980 N. An Orono biomechanical surface
11 tester (OBST) measured longitudinal shear and vertical force, whilst a traction tester
12 measured rotational shear after being dropped onto the surfaces. A weak, but significant,
13 linear relationship was found between rotational shear measured using the GWTT and
14 longitudinal shear quantified using the OBST. However, only the GWTT was able to detect
15 significant differences in shear resistance between the surfaces. Future work should continue
16 to investigate the strain rate and non-linear load response of surfaces used in equestrian
17 sports. Measurements should be closely tied to horse biomechanics and should include
18 information on the maintenance condition and surface composition. Both the GWTT and the
19 OBST are necessary to adequately characterise all the important functional properties of
20 equine sport surfaces.

21

22 **Key Words**

23 Torque; shear; arena surface; slip; grip; footing

24 **Nomenclature**

DDFT	Deep digital flexor tendon	
D_{max}	Peak vertical displacement (GWTT)	(mm)
GWTT	Glen Withy torque tester	
$GRFH_{max}$	Peak longitudinal ground reaction force (OBST)	(kN)
$GRFV_{mean}$	Mean vertical ground reaction force (GWTT)	(N)
$GRFV_{max}$	Peak vertical ground reaction force (OBST)	(kN)
OBST	Orono biomechanical surface tester	
SDFT	Superficial digital flexor tendon	

SL	Suspensory ligament	
<i>Slip</i>	Horizontal displacement from impact to $GRFV_{max}$ (OBST) calculated from double integration of $GRFH$	(mm)
T_{max}	Peak torque (GWTT)	(Nm)
T_{maxTT}	Maximum recorded torque (traction tester)	(Nm)

25

26 **1 Introduction**

27 The loading of surfaces by horse hooves is complex due to both the range of gaits and speeds
28 and the manoeuvres performed by the horse and the diverse characteristics of the different
29 surfaces. The functional properties of racetrack surfaces have been studied extensively
30 (Peterson, Roepstorff, Thomason, Mahaffey, McIlwraith, 2012; Ratzlaff, Hyde, Hutton,
31 Rathgeber, Balch, 1997; Reiser, Peterson, McIlwraith, Woodward, 2000; Setterbo, Fyhrie,
32 Hubbard, Upadhyaya, Stover, 2012) but less is known about the characteristics of arena
33 surfaces that are often used for non-racing equestrian sports which involve a more diverse
34 range of athletic activities and hoof surface interaction patterns. In nearly all cases surfaces
35 used for equestrian sports are both highly non-linear and strain rate dependent. For instance,
36 the surface response when executing a canter pirouette in a dressage competition may be
37 quite different to a quick turn during the jump off of a show jumping competition. As the
38 load on the surface increases the typical riding surface increases in stiffness (Reiser et al.,
39 2000) and, in general, the surface will also become stiffer as the load is applied at a higher
40 rate (Setterbo et al., 2012). Since shear resistance of a surface is directly related to the
41 surface stiffness, the grip characteristics are also expected to change with load and loading
42 rate. Thus, there is a need to understand the responses of arena surfaces to both the speed and
43 magnitude of loading, as the stiffness and shear resistance of the surface will influence both
44 the horse's ability to perform and the risk of it receiving an injury.

45
46 Shear resistance relates to the frictional forces that are generated between the hoof and the
47 surface and to friction between the particles within the surface (Hobbs et al., 2014). Linear
48 shear resistance affects sliding of the hoof across the surface in a horizontal plane especially
49 during braking phase of stance in straight-line movement. It also affects resistance of the
50 surface when the hoof is in an angled position relative to the ground, as found during push off
51 and sharp turns. Rotational shear resistance affects rotation of the hoof into the surface
52 material, which is also seen during push off and sharp turns. The sliding of the hoof on the
53 surface can either occur between the shoe and the surface, or within the material beneath the
54 hoof depending on the specific characteristics of the surface and the design of the shoe. In
55 addition, the forces generated by the horse's musculotendinous system tend to rotate the hoof
56 into a toe-down orientation within the surface material as the limb generates propulsion
57 (Thomason & Peterson, 2008). The surface must provide sufficient resistance to the
58 horizontal sliding motion or rotation of the hoof to enable the horse to obtain grip, which

59 prevents slipping, tripping or falling (Murray, Walters, Snart, Dyson, Parkin, 2010a) and
60 provides traction for propulsive effort (Crevier-Denoix et al., 2010). Excessive resistance to
61 the horizontal motion or rotation is expected to result in an earlier onset of hoof braking and
62 an increase in the magnitude of the peak stress and loading rate in the limb (Gustås, Johnston,
63 Drevemo, 2006). Reduced horizontal motion of the hoof has been associated with surface
64 hardness (Wilson & Pardoe, 2001; Orlande, Hobbs, Martin, Owen, Northrop, 2010) and
65 harder surfaces tend to increase the magnitude of higher frequency vibrations during impact
66 and limb loading (Chateau et al., 2009). The high frequency components of the loading are
67 reported to be attenuated mainly by the hoof, and the magnitude of peak stress is gradually
68 damped proximally by the distal limb structures (Lanovaz, Clayton, Watson, 1998;
69 Willemen, Jacobs, Schamhardt, 1999). High frequency loading damages bone and articular
70 cartilage predisposing to the development of osteoarthritis (Folman, Wosk, Voloshin, Liberty,
71 1986). Insufficient friction and shear resistance can lead to excessive slip and shearing of the
72 top layers of the surface during braking, limiting the traction available for propulsion.
73 Excessive slip during braking causes the horse to reduce stride length as a means of reducing
74 the longitudinal braking force (Chateau et al., 2010) which adversely affects performance. It
75 may also result in rider falls and accidents (Crevier-Denoix et al., 2010; Murray et al.,
76 2010a). Insufficient friction and shear resistance can lead to shearing of the top layers of the
77 surface and result in increased rotation of the hoof into the surface. Excessive slip will then
78 occur during braking, and traction will be lost for propulsion, which is known to increase
79 fetlock joint extension (Crevier-Denoix et al., 2010). Conversely, during midstance maximal
80 fetlock joint extension is reduced which is likely to reduce the storage and release of passive
81 strain energy in the superficial digital flexor tendon (SDFT) and the suspensory ligament
82 (SL) (Crevier-Denoix et al., 2010). The deficit in passive strain energy is proposed to be
83 compensated by a greater active contribution of the deep digital flexor (DDF) muscles to
84 maintain speed (Crevier-Denoix et al., 2010). Early onset of fatigue in the DDF muscle
85 results in greater passive strain of the SDFT which is then at risk of overloading and injury
86 (Butcher et al., 2007). High quality artificial and natural surfaces are needed for equestrian
87 sports in order to provide an appropriate balance between injury reduction and optimal
88 performance of the equine athlete. Shear resistance of the surface is a complex and important
89 factor in this equation and one that has not been adequately evaluated, in part due to a lack of
90 equipment that has been validated to measure shear resistance of arena surfaces.

91

92 Until recently decisions on the design and composition of equine arena surfaces have been
93 based almost entirely on anecdotal observation. This approach has continued in spite of the
94 growing evidence that surfaces can have a major effect on both the performance and the
95 incidence of injury in dressage horses (Murray, Walters, Snart, Dyson, Parkin, 2010b) and
96 eventers (Murray, Singer, Morgan, Proudman, French, 2006) which is similar to the link
97 between surfaces and injuries in racehorses (Oikawa & Kusunose, 2005; Parkin et al., 2004;
98 Peterson, McIlwraith, Reiser, 2008). Thus the development of reliable equipment that can
99 simulate equine movement and loading patterns to quantify the functional characteristics of
100 arena surfaces *in situ* is a vital step towards a process for assessment of equine arena surfaces
101 and developing standard methods to ensure consistency across different competition venues.
102 A drop-hammer system, the Orono biomechanical surface tester (OBST) was developed for
103 measuring racetrack properties (Peterson et al., 2008). The OBST has subsequently been
104 modified for use in the evaluation of equine arena surfaces (Northrop, Martin, Holt, Owen,
105 Hobbs, 2014) and for controlled experiments in the UK by the RACES research team (Holt,
106 Northrop, Owen, Martin, Hobbs, 2014). The apparatus was designed to mimic the loading
107 phase of the gait cycle in a galloping horse. It has two axes of motion that allow measurement
108 of both vertical force and linear shear resistance as the simulated hoof lands and is forced
109 across the surface (Peterson & McIlwraith, 2008). The OBST measures linear shear
110 resistance, but not rotational shear resistance, which may also vary (Nigg & Yeadon, 1987;
111 Setterbo, Yamaguchi, Hubbard, Upadhyaya, Stover, 2011). The drawback to using the OBST
112 to test arena surfaces is that it is designed to replicate the loads and speeds of a horse's
113 forelimb at the gallop (Peterson et al., 2008), or when landing from a jump, but it is not well
114 suited to the lower strain rates associated with slow gaits and rotational movements, such as
115 the dressage canter pirouette.

116

117 In human sports an apparatus for measuring rotational traction and friction of turf sports
118 pitches was originally designed in 1975 (Canaway & Bell, 1986). The studded-boot
119 apparatus, known as a torque tester, is now the internationally accepted device used in a
120 number of sports to ensure safety and performance (Twomey, Otago, Ullah, Finch, 2011). In
121 2010 a traction tester was adapted for use on equine surfaces by replacing the football studs
122 with a studded horse shoe (Blundell, Northrop, Owen, Lumsden, 2010). This device was
123 used for comparison in the present study, however, the apparatus is not considered to be
124 representative of the way a horse lands or turns on a surface, due to the low mass, low
125 vertical drop height and the turning procedure used. Concerns also exist related to the

126 applicability of the test even for human athletes. In particular, significant variation was
127 reported between operators (Blundell et al. 2010), which has been addressed by providing
128 automatic control of the speed of the turning and positioning of the studded disk (McNitt,
129 Middour, Waddington, 1997; Roche, Loch, Poulter, Zeller, 2008). The modified traction
130 tester measures linear and rotational traction simultaneously (Brosnan, McNitt, Serensits,
131 2009). However, neither design has been adapted for the speed and loads associated with the
132 equine athlete.

133

134 Other methods for assessing the horizontal properties of equine surfaces have included
135 cadaver limbs attached to a drag apparatus instrumented with load cells (Clanton, Kobluk,
136 Robinson, Gordon, 1991) and more recently a track testing device that measured linear shear
137 resistance and a shear vane tester that measured shear stress and surface cohesion (Setterbo et
138 al., 2012). The latter of these designs (Setterbo et al., 2012) has been used to make
139 measurements on dirt and synthetic racetracks, but both designs were reported to have
140 limitations in relation to replicating equine locomotion. Shear resistance on turf racetracks is
141 normally measured using a GoingStick (Caple, James, Bartlett, 2012), where a flat blade is
142 pushed into the surface and then rotated about its base to an angle of 45° to measure the force
143 needed to push and turn the blade (Peterson et al., 2012). A linear relationship between shear
144 resistance using a GoingStick and peak torque resistance using a studded disk apparatus was
145 found on turf sport pitches (Caple et al., 2012). This relationship has only been investigated
146 on turf surfaces which have a relatively homogeneous cross section that is necessary for the
147 health of the turf. This is usually not the case with racing surfaces (Mahaffey, Peterson,
148 McIlwraith, 2012) or with arena surfaces composed of fibre and sand (with or without the
149 addition of wax). In these surfaces a hard pan layer is set up under the shallow top surface
150 that supports the hoof during propulsion or landing. The non-homogeneity of these surfaces
151 makes them unsuitable for evaluation using a penetrometer type device such as the
152 GoingStick for measuring shear resistance.

153

154 An appropriate mechanical apparatus for measuring the rotational shear properties of equine
155 sport surfaces is not available. Current methods used in human biomechanics do not
156 adequately represent the hoof-surface interaction and current equine specific measurements
157 do not measure rotational shear. For this reason a new piece of equipment, named the Glen
158 Withy torque tester (GWTT), was designed that was capable of measuring rotational torque
159 whilst under a consistently applied quasi-static vertical load. The device is named after its

160 designer which provides the potential for it to become a piece of standardised equipment in
161 the future. This study compares data from the GWTT with data from other equipment used
162 to test arena surfaces (OBST and traction tester) to assess its ability to provide distinct
163 information describing the equine arena surface response. In addition, by using different
164 pieces of equipment, that apply different loading rates, the effect of strain rate dependency on
165 shear resistance can be explored. The aims of the study were to use the GWTT for measuring
166 equine arena surfaces and to compare its results with those from the OBST and traction tester
167 within and between surfaces. Linear and rotational shear resistance may vary for the same
168 surface (Nigg & Yeadon, 1987), and arena surfaces are reported to be strain rate dependant. It
169 was therefore hypothesised that any relationship between measurements from the OBST
170 compared to the GWTT and traction tester for the same surface, in particular measures of
171 rotational and longitudinal shear, would be non-linear and complex and would not be
172 expected to be well correlated. Also, even if a correlation between these devices was
173 observed on a particular surface it would not necessarily be applicable to other surfaces.
174 Therefore, the initial investigations using the GWTT and the other devices were performed
175 using two different types of surfaces.

176

177 **2 Methods**

178 The construction and measurements made by the traction tester and a first-generation OBST
179 have been previously described (Blundell et al., 2010; Peterson et al., 2008). In this work, we
180 give construction details of the GWTT, and describe the types of measurement that are made
181 by the traction tester, GWTT, and arena-surface modified OBST. The three devices are
182 shown in Fig. 1.

183

184 **2.1 Equipment**

185 2.1.1 Glen Withy Torque Tester (GWTT)

186 The GWTT is an instrumented hoof design built into a support structure that can carry up to
187 100 kg mass and that has suitable attachments for a tractor or similar sized equipment to
188 move it easily. The support structure of the GWTT was based on a vertical central column
189 and horizontal cross member of 75 mm box section (see Figure 1). The central column houses
190 a 25 mm diameter main shaft that rotates on ball bearing races (47 mm outer diameter (o.d.))
191 at the top and bottom of the shaft. In addition, 2 ball bearing thrust races (50 mm o.d. at the
192 top and 100 mm o.d. at the bottom) carry the vertical thrust force. Attached to the bottom of

193 the main shaft is a housing that sandwiches a piezoelectric dynamometer (Kistler Instruments
194 Ltd. Hook, Hampshire, UK, model 9271A; model 9272 is the currently available equivalent),
195 through which applied vertical force and dynamic torque are applied and measured
196 respectively. A horseshoe is fixed to the bottom of the housing at the base. At the top of the
197 main shaft is a square fitting drive to which a two-ended handle can be secured when in use
198 to provide complementary torque. The amount of rotational twist is measured by a dial
199 indicator fitted to the square section. The housing of the central column supports adjustable
200 bars on both sides to allow easy attachment and removal of circular masses. A control box to
201 house the instrumentation is also secured to the central column. The horizontal cross member
202 is designed to be attached to the bottom two links of a type 1 three-point tractor implement
203 linkage. Attached to the cross member is a spring loaded linear potentiometer (Novotechnik,
204 Ostfildern, Germany, model TRS 100) with a foot at its base and this measures the vertical
205 displacement of the horseshoe into the surface as torque is applied. An attachment on the
206 column for the top tractor link of the three-point linkage is also provided (see supplementary
207 materials for assembly drawings). Once the GWTT is secured in the three-point-linkage
208 vertical stability can be maintained, but with sufficient slack to prevent resistance at the links
209 during testing which might otherwise influence the torque measurements. To obtain dynamic
210 measurements the equipment is lowered slowly to the ground on the three point linkage, once
211 slack against the links the handle is turned through a measured angle by the same operator
212 and then raised immediately after turning is complete. Typical hoof rotations during
213 locomotion are shown in Fig. 2, which highlights the point in the stance phase most relevant
214 to the operation of the equipment.

215

216 Three different masses were examined as part of the GWTT validation process. The mass of
217 the apparatus was 16 kg, which was used as a baseline measurement. Addition of a 30 kg
218 mass (total 46 kg) was selected as being equivalent to the mass used by the traction tester
219 (Blundell et al., 2010). Addition of a 100 kg mass (total 116 kg) was used which provided
220 approximately half the mass of a pony and one fifth the mass of a horse. Three turning angles
221 (40° , 90° , 140°) were selected to give an indication of the effect of turning by different
222 degrees on the variability of the data produced by the apparatus. The minimum angle of 40°
223 was chosen to represent the rotation of the horse's body about a grounded limb, for example
224 during a canter pirouette where the leading hind limb is in contact with the ground for almost
225 80% of the stride (Burns & Clayton, 1997). As maximum torque is normally produced prior
226 to shear failure, turning the GWTT through the maximum possible angle ensured that the

227 separate events of shear failure and maximum torque were most likely to be captured. While
228 the central column was able to be turned through an angle more than 140°, a maximum angle
229 of 140° was used. A rotation of the device of 90° provided an intermediate value. Turning
230 speed was estimated and reproduced through practice and repetition of the same operator.

231

232 The voltage signals from the dynamometer were amplified (Kistler Instruments Ltd. Hook,
233 Hampshire, UK, charge amplifier model 5073) and these, together with the linear
234 potentiometer signals were then converted to a digital signal (National Instruments UK,
235 Newbury, Berkshire, UK, A/D converter model NI USB-6210). All were sampled
236 simultaneously for 10 s at 100 Hz in Labview (National Instruments UK, Newbury,
237 Berkshire, UK). Peak torque (T_{max}), peak vertical displacement (D_{max}) and mean vertical force
238 (GRF_{mean}) were extracted from the digital data acquired using the device.

239

240 2.1.2 Traction Tester

241 The traction tester is a simple design that uses a steel rod attached to a circular, screw-on base
242 with a studded horseshoe on the underside of the base (Fig. 1). Three circular, 10 kg masses
243 each with a central hole are secured to the rod above the base. Two handles at the top of the
244 apparatus allow it to be lifted and dropped. The operator lifted the device to a height of 0.2 m
245 before releasing it, to allow the horseshoe to embed into the surface. Once the apparatus had
246 been dropped, a torque wrench was applied to the top of the rod and then was rotated until
247 shear failure of the surface occurred. The maximum value recorded (T_{maxTT}) on the torque
248 wrench prior to failure was tabulated for each trial. The same experienced researcher was
249 used throughout to reduce variability, consistent with general practice (Blundell et. al, 2010).

250

251 2.1.3 Orono Biomechanical Surface Tester (OBST)

252 The operation of this apparatus has been described previously (Peterson et al., 2008). For
253 these tests the hoof was dropped through a distance of 0.86 m down the rails which were at
254 an angle of 8° from the vertical. Temporal data from a tri-axial load cell (Kistler Instruments
255 Ltd. Hook, Hampshire, UK, type 9347C) and string potentiometer (Celesco, Chatsworth, CA,
256 USA, model PT5A) were recorded simultaneously (National Instruments UK, Newbury,
257 Berkshire, UK, A/D converter model NI USB-6210) for 2 s in Labview at 2000 Hz (National
258 Instruments UK, Newbury, Berkshire, UK). The files were converted to a suitable ASCII
259 format and then imported into Visual 3D. Landing force was determined from the vertical
260 component of force from the tri-axial load cell using a threshold of 50 N and peak vertical

261 force from the maximum value recorded ($GRFV_{max}$). Landing speed was derived from the
262 string potentiometer displacement data and the longitudinal component obtained using
263 trigonometry. Slip distance was then measured by double integration of the longitudinal
264 component of force, where the force was divided by mass prior to the first integration and
265 landing speed was used as a constant for the second integration. Slip distance during loading
266 (Slip) was then measured from landing to peak vertical force. The longitudinal force
267 component was rectified and the maximum value identified to obtain peak longitudinal force
268 ($GRFH_{max}$).

269

270 **2.2 Initial validation of GWTT measurements**

271 2.2.1 Procedure

272 A calibration measurement of the coefficient of friction of the GWTT shoe on black mild
273 steel plate was carried out in the laboratory using a calibrated 8 camera Qualisys Oqus system
274 capturing data at 100 Hz. Markers were attached at the top and bottom edge of a 1 m flat
275 black steel plate and four markers were attached to the underside of a shoe made for the
276 GWTT. Trials were captured as the shoe slid down the angled steel plate with the angle of the
277 plate being varied in small increments from trial to trial to provide data that included
278 speeding up, constant velocity and slowing down. Ten tests were recorded with the open end
279 facing up the slope and a further 10 tests with the open end facing down the slope. The angle
280 was varied for each trial. In addition, four repeated measurements of the angle required to
281 initiate movement of the shoe were recorded in four different orientations of the horse shoe;
282 front, back, left, right.

283

284 Measurement of the coefficient of friction of the GWTT shoe on black mild steel was carried
285 out in-situ using the GWTT and a flat black mild steel plate with steel grips welded to the
286 underside. This plate was firmly secured into an arena surface prior to testing. The GWTT
287 was loaded with 100 kg mass, lowered onto the steel plate and rotated slowly through 90° and
288 the load removed following turning. Eight repeated measurements were recorded.

289

290 2.2.2 Data Analysis

291 For the laboratory based measurements, markers on the flat plate and the shoe were tracked
292 and exported to Visual 3D. The angle of the plate was determined from the marker
293 coordinates and the shoe velocity during sliding was derived. Average acceleration was
294 calculated over the last third of the slope. The coefficient of friction was determined by

295 calculating the tangent of the angle. Static friction mean and standard deviation (s.d.) were
296 tabulated. Linear regression was used to determine the coefficient of friction value at zero
297 acceleration for sliding friction.

298

299 For *in-situ* measurements T_{max} and GRF_{mean} were extracted from the GWTT and the frictional
300 force calculated from the shoe dimensions. The coefficient of friction was calculated by
301 dividing the frictional force by GRF_{mean} . Mean and s.d. were calculated and results from the
302 *in-situ* test were compared to the laboratory sliding friction results.

303

304 **2.3 In-situ testing of GWTT, OBST and traction tester**

305 *2.3.1 Procedure*

306 Two artificial surfaces were used; a waxed sand and fibre surface and a non-waxed sand and
307 fibre surface. Each surface was tested using 5 repeats at 9 locations with each piece of
308 equipment separately (see Fig. 3). The order of testing of additional mass (0, 30 and 100 kg)
309 and turn angle (40°, 90° and 140°) was randomised.

310

311 A surface sample was also taken from each location. The top layer of surface was removed
312 and a minimum of 100 g of sub-surface was placed into a labelled plastic bag and sealed. To
313 evaluate moisture content 100 g of the surface from each sample was weighed out and placed
314 in a pre-weighed heat-proof tray that was baked in an oven at 38 °C for 48 h. The samples
315 were then re-weighed and the moisture content determined using ISO/TS 17892-1:2004.

316

317 Three temperature loggers (Gemini Data Loggers, Chichester, West Sussex, UK, model
318 Tinytag Talk 2) were utilised in the week prior to data collection. One was placed 100 mm
319 below the surface of the test track, one was placed on top of the surface, and the third was
320 placed above the surface to measure the air temperature. The loggers were programmed to
321 record temperature every 10 min. The mean temperature \pm standard error in each position
322 was calculated for the week leading up to data acquisition. The measurements of moisture
323 for the unwaxed surface and temperature for the waxed surface are consistent with data
324 reported in the relevant literature (Bridge, Peterson, McIlwaith, Beaumont, 2010; Ratzlaff et
325 al., 1997). However, for consistency both temperature and moisture were measured for both
326 surfaces.

327

328 *2.3.2 Data Analysis*

329 Statistical analyses were performed in SPSS (IBM Corp., Armonk, NY, USA) with
330 significance set at $P < .05$. Data were screened for normality using a Kolmogorov-Smirnov
331 test. To identify the most appropriate protocol for use of the GWTT in relation to applied
332 load and turn angle, a 3 (mass) x 3 (turn angle) MANOVA was used with T_{max} and D_{max} as
333 dependant variables with Bonferroni post hoc tests on significant variables. To investigate
334 consistency of loading the limits of agreement between applied load and GRF_{mean} when
335 separated by mass and turn angle were determined (Bland & Altman, 1999). To evaluate the
336 relationship between measurements 1) on the same surfaces and 2) between surfaces made by
337 each piece of equipment, a partial correlation controlling for significant factors identified in
338 the MANOVA was used and 1) controlling for surface and 2) without controlling for surface.
339 Finally, a MANOVA was used for all measurements to compare the difference between the
340 two surfaces, with mass as a covariate. Stratified bootstrapping (1000 samples) was used on
341 all non-normally distributed measurements when conducting parametric tests.

342

343 **3 Results**

344 A typical raw data file is shown in Fig. 4 from the GWTT. Data were normally distributed for
345 D_{max} , T_{max} and *Slip*. All other data were not normally distributed. The coefficient of sliding
346 friction determined from the lab-based testing was 0.196 ± 0.006 (mean \pm C.I.) (see Fig. 5) and
347 for *in-situ* testing was 0.173 ± 0.021 (mean \pm s.d.) for the shoe on black steel plate. The
348 coefficient of static friction was 0.238 ± 0.018 (mean \pm s.d.).

349

350 The moisture contents for the waxed surface and non-waxed surface were 5.1 ± 2.11 % and
351 17.8 ± 1.68 % respectively (mean \pm s.d.). Air temperature, surface temperature and sub-surface
352 temperature in the week leading up to data collection measured in and above the waxed
353 surface were 19.5 ± 0.1 °C, 22.5 ± 0.2 °C, and 20.2 ± 0.1 °C respectively. Weather conditions
354 were considered to be temperate on the day of testing and there was no rainfall.

355

356 Mean \pm s.d. results for T_{max} and D_{max} with respect to mass and turn angle for the GWTT, for
357 both surfaces combined, are shown in Table 1. A significant main effect ($P < .001$) of mass
358 was found in the model with significant differences for both T_{max} $F(2) = 582.227$, $P < .001$ and
359 D_{max} $F(2) = 6.754$, $P = .002$. No significant differences were found for turn angle and there was
360 no significant interaction between mass and turn angle.

361

362 The limits of agreement between GRF_{mean} and the applied load separated by mass are shown
363 in Fig. 6 together with the percentage of measurements that fell outside of ± 1 s.d. limits for
364 each turn angle. The mean difference between measurements was -94.3 ± 46.2 , -75.0 ± 106.3
365 and -23.1 ± 75.5 N for 0, 30 and 100 kg masses respectively. A turn angle of 40° was most
366 often outside of the limits of agreement followed by 140° .

367

368 The relationship between measurements is shown in Table 2. When controlling for mass, a
369 weak negative relationship was found between D_{max} from the GWTT and T_{maxTT} from the
370 traction tester ($R = -.257$, $P = .019$). A weak positive relationship was found between D_{max} and
371 $Slip$ ($R = .234$, $P = .033$). No other relationships between variables were found.

372

373 Measurements for all equipment (mean \pm s.d.) are shown in Figure 7 separated by surface and
374 for the GWTT also separated by mass. A significant main effect ($P < .001$) was found for
375 surface with significant differences in T_{max} $F(1) = 12.38$, $P = .001$, D_{max} $F(1) = 10.57$, $P = .002$,
376 and $GRFV_{max}$ $F(1) = 15.37$, $P < .001$. No other measurements were found to differ significantly
377 between surfaces.

378

379 **4 Discussion**

380 This study examined the capability of a newly developed piece of equipment, known as the
381 Glen Withy Torque Tester (GWTT), to measure rotational torque on equestrian arena
382 surfaces. The most appropriate protocols were compared over a range of applied loads and
383 turn angles and measurements made with the GWTT were compared to measurements from
384 existing equipment used to evaluate arena surfaces. It was hypothesised that any relationship
385 between measurements, in particular that between $GRFH_{max}$, slip and T_{max} , would be non-
386 linear and complex. When pooling the data a weak, but significant linear relationship was
387 found between the GWTT and OBST, which measure rotational compared to linear shear
388 resistance and where markedly different loads and loading rates are applied to the surface.
389 This relationship weakened when controlling for surface. These findings suggest that the
390 hypothesis might, in part, be cautiously rejected when comparing linear slip to vertical
391 displacement of the GWTT into the surface, providing a sufficient number of data points are
392 compared to account for location specific variability. The lack of correlation between other
393 measurements from the GWTT compared to the OBST supported the hypothesis.

394

395 **4.1 Identification of the most appropriate protocol for the GWTT**

396 The mass applied to the GWTT had a significant effect on the T_{max} and D_{max} readings where a
397 greater mass was associated with higher values. Higher traction values have been measured
398 previously with devices suitable for testing sports surfaces when a greater vertical load was
399 applied due to the greater resistance to movement (Baker, 1991; Brosnan et al., 2009;
400 Goodall, Guillard, Dest, Demars, 2005; McNitt et al., 1997). When evaluating each
401 measured mass for reliability against the applied load, it was found that the minimum amount
402 of bias in measured mass occurred when 100 kg mass was attached to the GWTT. This may
403 be due to the attachment of the GWTT to a 3 point linkage where the heavier mass was more
404 stable once on the ground and as such it may have been easier to apply a rotational torque
405 without inadvertently altering the vertical force. The difference may also have been
406 influenced by spatial inconsistencies, which occur during the slide of the hoof on the surface
407 during the initial contact of the hoof on the arena. The resulting hoof prints and movement of
408 material are difficult to remove with maintenance, but the effect of the prints is reduced at
409 higher loads since the deeper levels of the surface which are measured at higher loads are not
410 impacted as much as the top surface of the arena.

411
412 Turning angle did not have a significant effect on T_{max} or D_{max} recorded with the GWTT, but
413 a 90° turn angle provided the most consistent vertically applied load compared to the other
414 two angles for all masses. For at 40° angle the mass may not have been as consistently
415 applied, due to the shorter time needed to make the turn before the GWTT was lifted again.
416 At 140° angle, the operator reported that it was difficult to achieve a consistent purchase on
417 the handle. A lack of control whilst rotating a traction device was responsible for low
418 reliability in measurements during a study by Twomey et al. (2011). This, in conjunction
419 with the angle not representing a particular activity carried out by horses, meant that using a
420 turning angle of 40° or 90° was more appropriate. One complete canter pirouette is usually
421 completed in 6-8 strides, which suggests that the body will turn through 45-60° over an inside
422 hind limb that is grounded for the majority of the turn if the movement is executed correctly
423 (Burns & Clayton, 1997). Similarly, a show jumping horse is expected to turn as tightly as
424 possible during the jump off round of a class (the jump off is a shorter version of the original
425 course and is to be completed as fast as possible). Crevier-Denoix et al. (2014) recently
426 reported that a pure static rotation of the hoof in the surface rarely occurs, as the hoof also
427 slides transversally and longitudinally throughout turning, which is not replicated by the
428 GWTT. In addition, GWTT does not simulate the loading conditions during propulsion. The

429 GWTT is rigid, simulating a turn of a planted foot under a quasi-static load, so further work
430 is required to investigate it's applicability to the biomechanics of turning. The results can be
431 considered as promising though with respect to the magnitude of peak torque (T_{max}), since
432 they were comparable with those found by Chateau et al. (2013) in horses trotting in circles
433 on different surfaces.

434

435 The accuracy of the measurements from the GWTT were compared to standard laboratory
436 tests for static and sliding friction of the shoe on black mild steel. The coefficient of static
437 friction for steel on steel with an oxide coating was reported to be 0.27 and for sliding friction
438 with a greasy surface 0.09 - 0.19 (Engineers Handbook, 2006). These values are comparable
439 with the laboratory based test results and *in-situ* test results obtained in this study, suggesting
440 that the GWTT provides sufficient accuracy of measurement for friction and shear resistance
441 when loaded with a 100 kg mass.

442

443 Turning speed was subjectively controlled in the current study. As the surfaces tested are
444 strain rate dependant (Reiser et al., 2000), small differences in turning speed may have
445 influenced measurements from the GWTT. The GWTT has since been instrumented with an
446 angular potentiometer (see supplementary information), which will allow turning speed to be
447 taken into account in future work. This will also allow for a more detailed examination of
448 maximum torque and shear failure events using higher sampling frequencies.

449

450 **4.2 Relationships between measurements**

451 The relationship between the vertical displacement of the GWTT (D_{max}) and slip measured
452 from the OBST suggests that more slip would be expected on a surface where the top layer
453 deforms more under an applied load. Greater deformation is usually associated with more
454 particle movement as a consequence of large pore spaces and less angularity in sand shape
455 (Bridge, Mahaffey, Peterson, 2014). Moisture content, polymer binder and fibre content are
456 also relevant. The relationship was thought to be weak due to the viscoelastic nature of the
457 surfaces, particularly as the moisture content varied between surfaces and across locations.
458 The surface specific increase in T_{max} with an increase in D_{max} suggests that rotational torque
459 increases as the shoe is displaced further into the surface vertically, possibly due to increasing
460 forces from the surrounding substrate (Burn, 2006). This contradicts the relationship found
461 between D_{max} recorded with the GWTT and T_{maxTT} measured using the traction tester, which
462 suggests that surfaces with greater vertical deformation offer less traction. An explanation

463 may relate to the difference in function between the devices. The traction tester tended to be
464 pulled out from the surface, whereas the GWTT tended to “screw down” into the surface. The
465 traction measurement may therefore be indicative of the looseness of the cushion, rather than
466 the shear strength of the surface as a whole. The disputed reliability of the traction tester may
467 also have influenced these results (Twomey et al., 2011). The surface specific relationships
468 found for the OBST show the intrinsic link between the components of force from a dynamic
469 impact and data derived from forces, in this case slip.

470

471 The lack of a relationship between other measurements highlights the complexity of arena
472 surface functional properties and their measurement. The need for truly functional
473 measurements of arena surfaces is therefore clearly supported by these results. These
474 surfaces usually have a loose upper layer which allows motion of the hoof early in the
475 loading phase supported by an underlying firm layer. This stratification accentuates the non-
476 linear character of the materials since the initial stiffness of the surface is very low but it
477 increases with an increase in the load. This increase in stiffness as a function of loading
478 occurs in both vertical and horizontal directions. At the same time the strain rate sensitivity
479 of the loading in shear is characteristic of a porous material where flow of water or wax is
480 highly dependent on the loading rate (Bridge, Peterson, McIlwaith, 2011). This supports the
481 principle that the loading of the surface must represent the rate and load of the hoof for the
482 particular usage of the surface.

483

484 **4.3 Comparison of surface behaviour**

485 Differences between the waxed and non-waxed surfaces were detected by the GWTT and the
486 OBST, but not the traction tester. However, only the GWTT was able to detect significant
487 differences between the surfaces in relation to shear resistance characteristics.

488

489 The significantly higher torsional resistance measurements and the significantly lower
490 displacement measurements for the waxed surface when compared with those for the non-
491 waxed surface (all obtained using the GWTT), indicates that the waxed surface exhibits
492 greater shear resistance than the non-waxed surface. Although not significant, the reduction
493 in slip for the waxed surface also suggests that this surface has more grip. In baseball playing
494 surfaces with higher soil bulk density levels are associated with significantly increased linear
495 and rotational traction (Brosnan et al., 2009), which is thought to be due to a higher soil bulk
496 density causing greater resistance to the movement of the athlete’s studs through the profile

497 (Brosnan et al., 2009). Less surface deformation together with reduced horizontal slip
498 distance was also found by Crevier-Denoix et al. (2013) when comparing horses cantering on
499 turf versus an all-weather waxed surface, but in this case the waxed surface had greater
500 deformation and slip. Chateau et al. (2009) also described an increased duration of the
501 braking phase on all-weather waxed sand compared to crushed sand. The wax component of
502 a surface may therefore be less of a determinant of shear resistance and grip than, for instance
503 the surface density. Surface density did not, however, affect the traction values recorded on
504 synthetic equine surfaces using the traction tester (Holt et al. 2014), although these findings
505 may simply indicate that the equipment is not appropriate for such measurements rather than
506 indicating the lack of a relationship between traction and bulk density.

507

508 The similarity of $GRFH_{max}$ between surfaces was also somewhat surprising, as greater
509 maximum horizontal force has been measured on crushed sand in comparison to an all-
510 weather waxed track in trotters wearing a dynamometric horseshoe (Robin et al., 2009). In
511 addition, similarity in $GRFH_{max}$ infers similarity in shear resistance and slip, which was not
512 found. One of the confounding factors in the study of slip and shear resistance was the
513 damping ability of the surface. Crevier-Denoix et al. (2013) reported that waxed surfaces are
514 more effective in damping lower frequency concussion events. As such, indirect
515 measurements of slip may be difficult to interpret alone. Using the horizontal force
516 measurements to determine slip appears to be more sensitive to changes in surface type for
517 the OBST, rather than considering horizontal forces alone.

518

519 When comparing the range of measurements taken from each surface it was also apparent
520 that greater variability was consistently found on the non-waxed surface. Wax is reported to
521 improve surface consistency by reducing the effects of moisture (Bridge, Peterson,
522 McIlwaith, 2012), which was relatively high in the non-waxed surface on the test date. In
523 addition, the fibre type and distribution through the surface may have influenced variability,
524 as longer fibres were evident in the non-waxed surface.

525

526 Using the GWTT it was also possible to calculate the coefficient of sliding friction, which
527 was found to be 0.40 ± 0.06 on the waxed surface and 0.37 ± 0.11 on a non-waxed surface.
528 These values are lower than the values of 0.585 to 0.741 reported when dragging cadaver
529 hooves across a dirt track (Clanton et al., 1991), and lower than for human sporting activities
530 (Shorten, Hudson, Himmelsbach, 2003). In the study by Clanton et al. (1991) the build up of

531 material in front of the hooves may have artificially increased the shear resistance. The
532 requirement for slide in equine activities is expected to be greater than in human activities.
533 Concrete, asphalt and rubber surfaces (smooth and patterned) have been shown to have a
534 static coefficient greater than 0.7, which limits the potential for hoof slip (McClinchey et al.
535 2004). Gustås et al. (2006) suggested that a high amount of friction during the hoof-surface
536 interaction increases vibration transients, resulting in mechanical stress to the structures of
537 the distal limb and possible injury, thus implying that a surface with a lower coefficient of
538 friction would be more favourable. Harder equine surfaces are commonly reported to have
539 increased grip, which does not support the $GRFV_{max}$ results compared to the results from the
540 GWTT. However, the $GRFV_{max}$ values are most likely to have been lower on the waxed
541 surface because the inclusion of a permavoid system in the sub-base has previously been
542 shown to significantly reduce peak vertical force using the OBST (Holt et al., 2014). This
543 highlights the need to use the OBST for measurement of the complete surface *in-situ*, as
544 many of the current measurement equipments are not capable of detecting differences below
545 the surface that the horse will experience.

546

547 **5 Conclusion**

548 In this study the GWTT was shown to be the only equipment tested capable of identifying
549 and measuring the difference in shear resistance of a waxed surface compared with a non-
550 waxed surface. This is an important consideration in equestrian sports for facilitating optimal
551 performance without compromising safety. Since the characteristics and performance of
552 arena surfaces are complex, it may be necessary to use more than one piece of equipment to
553 adequately characterise all the important functional properties. Based on the results presented
554 here data from the torque tester did not add significantly to the information provided by the
555 OBST and the GWTT. Future studies should carry out a more extensive evaluation of the
556 functional properties measured by the OBST and the GWTT to explore the complex
557 relationship between linear and rotational shear resistance under different loading conditions.

558

559 **Acknowledgements**

560 The authors would like to thank the University of Central Lancashire for funding a
561 studentship and providing the engineering resources needed to undertake this project. The
562 authors would like to thank Myerscough College for providing the test facilities used to carry
563 out *in situ* testing.

564

565 **References**

- 566 Baker, S. W. (1991). Temporal variation of selected mechanical properties of natural turf
567 football pitches. *Journal of Sports Turf Research Institute*, 67, 83-92.
- 568 Bland, J. M. & Altman, D. G. (1999). Measuring agreement in method comparison studies.
569 *Statistical Methods in Medical Research*, 8, 135-160.
- 570 Blundell, E., Northrop, A. J., Owen, A. G., Lumsden, P. J. (2010). The short and long-term
571 changes in mechanical properties of a synthetic equestrian surface. In *International Society of*
572 *Equitation Science Annual Conference*. Uppsala, Sweden, 44.
- 573 Bridge, J. W., Peterson, M. L., McIlwaith, C. W. & Beaumont, R. M. (2010). Temperature
574 Effects on Triaxial Shear Strength of Granular Composite Sport Surfaces. *Journal of ASTM*
575 *International*, (7) 9, 1 JAI103139.
- 576 Bridge, J. W., Peterson, M. L. & McIlwaith, C. W. (2011). Dynamic Strain Rate Response
577 with Changing Temperatures for Wax-Coated Granular Composites, Dynamic Behavior of
578 Materials, Volume 1. *Conference Proceedings of the Society for Experimental Mechanics*
579 *Series*, 1, 253-259.
- 580 Bridge, J. W., Peterson, M. L. & McIlwaith, C. W. (2012). The Effect of Temperature on the
581 Tangent Modulus of Granular Composite Sport Surfaces. *Experimental Techniques*, doi:
582 10.1111/j.1747-1567.2012.00851.x
- 583 Bridge, J. W., Mahaffey, C. A. & Peterson, M. L. (2014). Analytical test methods used to
584 characterize granular composite sports surface materials. *Applied Mechanics and Materials*
585 440, 74-81.
- 586 Brosnan, J. T., McNitt, A. S. & Serensits, T. J. (2009). Effects of varying surface
587 characteristics on the hardness and traction of baseball field playing surfaces. *International*
588 *Turfgrass Society Research Journal*, 11, 1-13.
- 589 Burn, J. F. (2006). Time domain characteristics of hoof-ground interaction at the onset of
590 stance phase. *Equine Veterinary Journal*, 38, 657-663.
- 591 Burns, T. E. & Clayton, H. M. (1997). Comparison of the temporal kinematics of the canter
592 pirouette and collected canter. *Equine Veterinary Journal*, 23, 58-61.
- 593 Butcher, M. T., Hermanson, J. W., Ducharme, N.G., Mitchell, L. M., Soderholm, L.V. &
594 Bertram, J. E. A. (2007). Superficial digital flexor tendon lesions in racehorses as a sequela to
595 muscle fatigue: A preliminary study. *Equine Veterinary Journal*, 39, 540-545.

596 Canaway, P. M. & Bell, M. J. (1986). Technical note: An apparatus for measuring traction
597 and friction on natural and artificial playing surfaces. *The Journal of the Sports Turf*
598 *Research Institute*, 62, 211-214.

599 Caple, M. C. J., James, I. T., & Bartlett, M. D. (2012). Using the GoingStick to assess pitch
600 quality. *Journal of Sports Engineering and Technology* 227(2), 83-90.

601 Chateau, H., Robin, D., Falala, S., Pourcelot, P., Valette, J.-P., Ravary, B., Denoix, J.-M. &
602 Crevier-Denoix, N. (2009). Effects of a synthetic all-weather waxed track versus a crushed
603 sand track on 3D acceleration of the front hoof in three horses trotting at high speed. *Equine*
604 *Veterinary Journal*, 41(3), 247-251.

605 Chateau, H., Holden, L., Robin, D., Falala, S., Pourcelot, P., Estroup. P., Denoix, J.-M. &
606 Crevier-Denoix, N. (2010). Biomechanical analysis of hoof landing and stride parameters in
607 harness trotter horses running on different tracks of a sand beach (from wet to dry) and on an
608 asphalt road. *Equine Veterinary Journal*, 42(38), 488-495.

609 Chateau H, Camus M, Holden-Douilly L, Falala S, Ravary B, Vergari C, Lepley J, Denoix
610 JM, Pourcelot P & Crevier-Denoix N. (2013). Kinetics of the forelimb in horses circling on
611 different ground surfaces at the trot. *The Veterinary Journal*, 198(1), e20–e26.

612 Clanton, C., Kobluk, C., Robinson, R. A. & Gordon, B. (1991). Monitoring surface
613 conditions of a Thoroughbred racetrack. *Journal of the American Veterinary Medical*
614 *Association*, 198, 613-620.

615 Crevier-Denoix, N., Robin, D., Pourcelot, P., Falala, S., Holden, L., Estoup. P., Desquilbet.
616 L., Denoix, J.-M. & Chateau, H. (2010). Ground reaction force and kinematic analysis of
617 limb loading on two different beach sand tracks in harness trotters. *Equine Veterinary*
618 *Journal Supplement*, 38, 544-551.

619 Crevier-Denoix, N., Pourcelot, P., Holden-Douilly, L., Camus, M., Falala, S., Ravary-
620 Plumioen, B., Vergari, C., Desquilbet. L., & Chateau, H. (2013). Discrimination of two
621 equine racing surfaces based on forelimb dynamic and hoof kinematic variables at the canter.
622 *The Veterinary Journal*, 198, e124-e129.

623 Crevier-Denoix, N., Camus, M., Falala, S., Ravary-Plumioen, B., Pauchard, M., Martino, J.,
624 Desquilbet, L., Chateau, H. & Pourcelot, P. (2014). 3D measurement of the displacement of
625 the forelimb hoof during stance in three horses circling at the canter on a competition surface.
626 *Computer Methods in Biomechanics and Biomedical Engineering*, 17, supplement 1, 142-
627 143.

628 Engineers Handbook (2006). Coefficient of friction. Engineers Handbook. Available at
629 www.engineershandbook.com/Tables/frictioncoefficients.htm, Accessed 25.10.14.

630 Goodall, S. A., Guillard, K., Dest, W. M. & Demars, K. R. (2005). Ball response and traction
631 of skinned infields amended with calcined clay at varying soil moisture contents.
632 *International Turfgrass Society Research Journal*, 10, 1085-1093.

633 Gustås, P., Johnston, C. & Drevemo, S. (2006). Ground reaction force of hoof deceleration
634 patterns on two different surfaces at the trot. *Equine and Comparative Exercise Physiology*,
635 3(4), 209-216.

636 Folman, Y., Wosk, J., Voloshin, A. & Liberty, S. (1986). Cyclic impacts on heel strike: A
637 possible biomechanical factor in the etiology of degenerative disease of the human locomotor
638 system. *Archives of Orthopaedic Traumatic Surgery*, 104, 363-365.

639 Hobbs, S. J., Northrop, A. J., Mahaffey, C., Martin, J. H., Clayton, H. M., Murray, R.,
640 Roepstorff, L. & Peterson, M. (2014). *Equine Surfaces White Paper*. FEI Publication.
641 Available at www.fei.org/fei/about-fei/publications/fei-books Accessed 25.10.14.

642 Holt, D., Northrop, A., Owen, A., Martin, J. & Hobbs, S. J. (2014). Use of surface testing
643 devices to identify potential risk factors for synthetic equestrian surfaces. *Procedia*
644 *Engineering*, 72, 949-954.

645 ISO/TS 17892-1:2004 (2004) Geotechnical investigation and testing – Laboratory testing of
646 soil – Part 1: Determination of water content. Available at
647 www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=38514 Accessed
648 25.10.14.

649 Lanovaz, J. L., Clayton H. M. & Watson, L. G. (1998). In vitro attenuation of impact shock
650 in equine digits. *Equine Veterinary Journal Supplement*, 26, 96–102.

651 Mahaffey, C. A., Peterson, M. & McIlwraith, C. W. (2012). Archetypes in Thoroughbred dirt
652 racetracks regarding track design, clay mineralogy, and climate. *Sports Engineering*, 15(1),
653 21-27.

654 McClinchey, H. L., Thomason, J. J. & Runciman, R. J. (2004). Grip and slippage of the
655 horse's hoof on solid substrates measured *ex Vivo*. *Biosystems Engineering*, 89(4), 485-494.

656 McNitt, A. S., Middour, R. O. & Waddington, D. V. (1997). Development and evaluation of
657 a method to measure traction on turfgrass surfaces. *Journal of Testing and Evaluation*, 25,
658 99-107.

659 Murray, J. K., Singer, E. R., Morgan, K. L., Proudman, C. J. & French, N. P. (2006). The risk
660 of a horse-and-rider partnership falling on the cross-country phase of eventing competitions.
661 *Equine Veterinary Journal*. 38(2), 158-163.

662 Murray, R. C., Walters, J. M., Snart, H., Dyson, S. J. & Parkin, T. D. H. (2010a).
663 Identification of risk factors for lameness in dressage horses. *The Veterinary Journal*, 184,
664 27-36.

665 Murray, R. C., Walters, J. M., Snart, H., Dyson, S. J. & Parkin, T. D. H. (2010b). How do
666 features of dressage arenas influence training surface properties which are potentially
667 associated with lameness? *The Veterinary Journal*, 186, 172-179.

668 Nigg, B. M. & Yeadon, M. R. (1987). Biomechanical aspects of playing surfaces. *Journal of*
669 *Sports Sciences*, 5 117-145.

670 Northrop, A. J., Martin, J. H., Holt, D, Owen A. G. & Hobbs, S. J. (2014). Development of
671 the equestrian arena surfaces for the 2012 Olympic Games. In *Ninth International*
672 *Conference on Equine Exercise Physiology*, Chester, UK.

673 Oikawa, M. & Kusunose, R. (2005). Fractures sustained by racehorses in Japan during flat
674 racing with special reference to track condition and racing time. *The Veterinary Journal* 170,
675 369-374.

676 Orlande, O., Hobbs, S. J., Martin, J. H., Owen, A. G. & Northrop, A. J. (2012) Measuring
677 hoof slip of the leading limb on jump landing over two different equine arena surfaces.
678 *Comparative Exercise Physiology*, 8(1), 33-39.

679 Parkin, T. D., Clegg, P. D., French, N. P., Proudman, C. J., Riggs, C. M., Singer, E. R.,
680 Webbon, P. M. & Morgan, K. L. (2004). Race- and course-level risk factors for fatal distal
681 limb fracture in racing Thoroughbreds. *Equine Veterinary Journal*, 36, 521-526.

682 Peterson, M. L. & McIlwraith, C. W. (2008). Effect of track maintenance on mechanical
683 properties of a dirt racetrack: A preliminary study. *Equine Veterinary Journal*, 40(6), 602-
684 605.

685 Peterson, M. L., McIlwraith, C. W. & Reiser, R. F. (2008). Development of a system for the
686 in-situ characterisation of thoroughbred horse racing track surfaces. *Biosystems Engineering*,
687 101, 260-269.

688 Peterson, M. L., Roepstorff, L., Thomason, J. J., Mahaffey, C. & McIlwraith, C. W. (2012).
689 Racing Surfaces. White Paper. Available at www.racingsurfaces.org/bulletins.html Accessed
690 25.10.14.

691 Ratzlaff, M. H., Hyde, M. L., Hutton, D. V., Rathgeber, R. A. & Balch, O. K. (1997).
692 Interrelationships between moisture content of the track, dynamic properties of the track and
693 the locomotor forces exerted by galloping horses. *Equine Journal of Veterinary Science*,
694 17(1), 35-42.

695 Reiser, R. F., Peterson, M. L., McIlwraith, C. W. & Woodward, B. (2000). Simulated effects
696 of racetrack material properties on the vertical loading of the equine forelimb. *Sports*
697 *Engineering*, 3, 1-11.

698 Robin, D., Chateau. H., Pacquet, L., Falala, S., Valetter, J.-P., Pourcelot, P., Ravary, B.,
699 Denoix, J.-M. & Crevier-Denoix, N. (2009). Use of a 3D dynamometric horsehoe to assess
700 the effects of an all-weather waxed track and a crushed sand track at high speed trot:
701 Preliminary study. *Equine Veterinary Journal*, 41(3), 253-256.

702 Roche, M., Loch, D., Poulter, R., Zeller, L. (2008). Measuring the traction profile on
703 sportsfields: Equipment development and testing. *Acta Horticulturae*, 881, 399-413.

704 Setterbo, J. J., Yamaguchi, A., Hubbard, M., Upadhyaya, S. K. & Stover, S. M. (2011).
705 Effects of equine racetrack surface type, depth, boundary area, and harrowing on dynamic
706 surface properties measured using a track-testing device in a laboratory setting. *Sports*
707 *Engineering*, 14, 119-137.

708 Setterbo, J. J., Fyhrie, P. B., Hubbard, M., Upadhyaya, S. K. & Stover, S. M. (2012).
709 Dynamic properties of a dirt and a synthetic equine racetrack surface measured by a track-
710 testing device. *Equine Veterinary Journal*, 45, 25–30.

711 Shorten, M., Hudson, B. & Himmelsbach, J. (2003). Shoe-surface traction of conventional
712 and in-filled synthetic turf football surfaces. In *XIX International Congress on Biomechanics*
713 Available at: [www.brock-international.com/docs/Shorten%20-
714 %20Traction%20study%2050mm%20turf%20.pdf](http://www.brock-international.com/docs/Shorten%20-%20Traction%20study%2050mm%20turf%20.pdf). Accessed 25.10.14.

715 Thomason, J. J. & Peterson, M. L. (2008). Biomechanical and mechanical investigations off
716 the hoof-track interface in racing horses. *Veterinary Clinics Equine Practice*, 24, 53-77.

717 Twomey, D. M., Otago, L., Ullah, S., Finch, C. F. (2011). Reliability of equipment for
718 measuring the ground hardness and traction. *Journal of Sports Engineering and Technology*,
719 225, 131-137.

720 Willemen, M. A., Jacobs, M. W. H. & Schamhardt, H. C. (1999). In vitro transmission and
721 attenuation of impact vibrations in the distal forelimb. *Equine Veterinary Journal*
722 *Supplement*, 30, 245–248.

723 Wilson, A.M. & Pardoe, C.H. (2001). Modification of a force plate system for equine gait
724 analysis on hard road surfaces: A technical note. *Equine Veterinary Journal Supplement*, 33,
725 67-69.

726
727
728

729
730
731
732
733
734
735
736
737
738
739
740
741
742
743
744
745

Figure Captions

746 **Fig. 1: Photograph of: a) the Glen Withy torque tester (GWTT), b) the Orono**
747 **biomechanical surface tester (OBST) and c) the traction tester.**

748

749 **Fig.2: Typical rotational (R) and longitudinal (L) motions of the hoof during the hoof-**
750 **surface interaction viewed laterally a) footstrike, b) secondary impact, c) breakover**
751 **where pitch rotation and longitudinal sliding occurs. Frontal and solar views of d) roll**
752 **rotation, and e) yaw rotation which is most likely to occur during turning and are**
753 **usually accompanied by longitudinal and/or medio-lateral sliding. The GWTT**
754 **replicates motion and torque as shown in e).**

755

756 **Fig. 3: Plan of the data collection area used to test each of the two surfaces. Each mass**
757 **and each turn angle were tested at one of the locations. The order was randomised. The**
758 **testing areas were marked using flags and were 3 m × 4 m in size.**

759

760 **Fig. 4: A typical graph from the GWTT. The graph illustrates signals for GRF_{mean} (the**
761 **average of vertical GRF values over the time illustrated (kN)), $D_{max} \times 10$ (mm), T_{max}**
762 **(Nm).**

763

764 **Fig. 5: Results of laboratory sliding friction tests showing the coefficient of friction value**
765 **for the shoe on black mild steel intersection of the x-axis at 0.196 ± 0.06 (mean \pm C.I.).**

766 **Fig. 6: Bland and Altman (1999) plot of the limits of agreement between GRF_{mean} from**
767 **the GWTT and the load applied ((machine mass + applied mass) x gravity) (N), a) 16 +**
768 **0 kg applied load, b) 16 + 30 applied load, c) 16 + 100 kg applied load. The dotted**
769 **horizontal lines show the limits of agreement at 1 standard deviation from the mean.**
770 **Data points outside of the dotted lines may be considered as inconsistencies in vertical**
771 **loading of the GWTT.**

772

773 **Fig. 7: Measured differences between surfaces for the GWTT: T_{max} (Nm), $D_{max} \times 10$**
774 **(mm); the OBST: $Slip$ (mm), $GRFH_{max}$ (kN), $GRFV_{max}$ (kN); and the traction tester:**
775 **T_{maxTT} (Nm). Error bars represent the standard deviation. * Significant differences**
776 **($P < .05$) were found for T_{max} and D_{max} and $GRFV_{max}$.**

777

778